A STUDY IN DESIGN

OF

A NUCLEAR-ELECTRIC GENERATING STATION

THESIS

Presented to the Faculty of the Graduate School of the Massachusetts Institute of Technology in Partial Fulfillment of the Requirements for the Degree of

MASTER IN ARCHITECTURE

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Sir:

I hereby submit the enclosed thesis, entitled "A Study in Design of a Nuclear-Electric Generating Station," in partial fulfillment of the requirements for the degree of Master in Architecture.

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ABSTRACT

Declining reserves of conventional fuels and increasing scarcity of hydro-electric sites for economic electric power production and the increasing demand for electricity combine to emphasize the importance of using the energy of nuclear fission for electric power production. The Atomic Energy Commission has estimated that between 35 and 140 nuclear power stations will be built by 1975. The design of a nuclear power station and the role the architect might play in its design thus seems an appropriate topic for study.

The material in the second chapter is included to give some familiarity with nuclear power processes as an aid in understanding the illustrative design presented later. This chapter is based on literature research only in the unclassified published material.

Chapter III is a description of the new field of Operations Research. The application of team research methods to the solution of problems amenable to quantitative determinations, the place of an architect on such a team, and his use of its findings are discussed.

In Chapter IV a planning and design organization is postulated, and the principal planning problems associated with a nuclear power station are discussed.

Studies of planning problems are presented in the

fifth chapter, leading to selection of a site, determination and analysis of the personnel organization and space requirements for an illustrative station design.

In Chapter VI the arrangement of the major building and equipment components of a nuclear station is discussed in illustrative studies. Conclusions reached in these studies are applied in the illustrative design.

The drawings and brief descriptions of an illustrative design for a nuclear power station are presented in Chapter VII. Conclusions reached as the result of research undertaken for this thesis are stated at the end of the chapter.

CHAPTER I

INTRODUCTION

Electric Power and Nuclear Power Stations

We of the United States rely heavily on our industrial prowess and capability. It has been said that our characteristic art form is our technology. One reason for this advanced industrial technology can be found in our available resources of power and raw materials.

During much of the formative period of American industry, water power figured prominently. Early plants which converted water flow directly to mechanical power were superseded by hydro-electric generating stations and fuel-burning generating stations. The demand for electric power has led to construction of the large-scale central station steam-electric plants and the integrated systems of the present age.

The availability of fuels has become an important speculation because of the tremendous industrial growth in progress and prospect. Studies of the resources of fuels and of the hydro-electric power potential of the country's watersheds show no critical shortages for the near future, but a picture of dwindling energy supplies for presently used conversion methods. Thus, any new energy resources assume importance for our industrial future.

The possibility of harnessing energy for electric power production is bright. With the realization of current research and development programs of government and industry and the successful construction and operation of those nuclear-electric plants already proposed by utilities, economic electric power from nuclear energy should be feasible.

Importance of the Problem

Many large industrial concerns and utilities have become interested in nuclear-electric power in recent years. However, since many of the feasibility studies have never advanced to the stage of building and structures design, information on building for nuclear installations is limited.

In view of the vital need for electric power in our industrialized economy, of the dwindling supplies of presently used energy sources, and of the lack of precedents for the building aspects of nuclear stations, a study of the problem seems timely and important.

Is It Architecture?

The design of a power station is a complex problem involving many skills. The systems involved are the province of engineers and scientists well trained in basic and applied scientific fields. Is the problem then the concern of the architect? This writer believes it is, for the following reasons:

1. The principal common requirement for the several systems of a power station is that of structurally articulated space. Thus the system design specialists must depend on a building designer to provide space, support, and enclosure.

This requirement is properly the responsibility of the architect and his collaborators in site, building, and structural design.

2. The complexity and large scale of a power station design requires coordinated action of the necessary specialists, if other than chaos is to result. They are commonly the collaborators of the architect. The scope and complexity of architectural work ensures that the architect is a competent coordinator and job manager.

The Viewpoint

Architecture is commonly considered as the art and science of building to house human life and activities. In a larger sense, architecture is the embodiment of organization and structure. In either sense, architecture is the expression of its age and civilization.

Evolution of Architecture

Throughout most of the history of architecture, the planning and construction of buildings was a reflection of the personal experience of the designer and craftsman, either gained directly, or inherited through the apprentice system. This method of building by experience, although slow and inflexible, was responsible for the consistency which we find in periods of the past.

Since the beginnings of scientific advancement and the ensuing industrial revolution, direct experience has no longer been so essential to knowledge. Structural theory and analysis have helped to free architects from the imitation of past experience. Improvements in communications have ensured that the entire past and present is available for reference. Because of these changes buildings have become more diversified and the work of their designers many times more difficult.

The twentieth century has seen the filling-in of large voids in scientific knowledge and tremendous strides in applications of investigative science. Rapid advances in transportation and industrial progress have stimulated progress in structural techniques and in materials and methods of construction. The impact of political change on the art and science of building has been vast; freedom and improvement of living standard capabilities have resulted in great demand for the qualities which architecture can offer. An entire new field of architecture has grown up -- that of structures and buildings for industrial processes and equipment -- which in some cases has only small direct concern with human beings. These demands severely tax any concept of design by experience.

Here stands the architect of today. The tremendous advances made by the past few generations have made available to him a bewildering array of tools and techniques. The rise of scientific knowledge and specialization of other fields has resulted in his being surrounded by an ever-increasing group of design specialists as collaborators.

The Future

As the impact of industry and economics on our way of life increases, the concern of architecture with the methods of science must increase accordingly if architecture is to continue as an expression of the age. The trend seems clearly to be away from the master builder concept of an architect's position and toward a more workable alliance between collaborating specialists. One such possibility is presented in Chapter III.

Conditions for an Industrial Architecture

Geoffrey Scott discusses the three conditions for an architecture: commodity, firmness, and delight. He defines firmness as the constructive quality; a rational scientific condition which deals with physical science -- its laws and materials. Commodity, the adaptation of architecture to its purpose, is described by Scott as the expression of human life and needs, as opposed to science. The present-day broader concern with science will permit considering commodity as also an expression of science insofar as human life and its needs can be adjudged rational and scientifically significant. (The social and life sciences are removing much of the uncertainty and mystery from the needs and deeds of men, at least on a group behavior basis.) Delight is, as described by Scott, a purely esthetic impulse and desire, "the disinterested desire for beauty," and thus pure art.[1]

If firmness and commodity are considered as the useful (as opposed to the esthetic) conditions or variable factors in

[1] Geoffrey Scott. The architecture of humanism (2d ed., 1924), 15-18.

the mathematical sense, of an architectural problem, then the <u>useful value</u> of a solution to the problem must be a function of these factors and thus determined by the values they assume. Further, the number of solutions obtainable is governed by the severity of the boundary limitations, or restraints, on the factors. To illustrate, for a given set of <u>commodity</u> (functional) restraints, a number of solutions to a problem are possible. For a particular functional (spatial) arrangement, constructive solutions using wood or reinforced concrete would have approximately the same <u>commodity</u> value; their <u>firmness</u> (constructive) values would be different, however. If the only limitations on construction were stability and shelter both solutions would be satisfactory. If, however, a further restraint of fireproofness was imposed, only the concrete solution would satisfy.

<u>Delight</u> must be considered separately from the <u>useful</u> values of the solution, as an <u>esthetic</u> value. Thus solutions found to be acceptable according to functional and constructive restraints can be evaluated further according to their esthetic worth.

It is obvious that there are more restraints on function and construction in large and complex projects than in smaller scale ones. The result is that for the smaller projects there exists a relatively large region of acceptable <u>useful</u> solutions, while for the large and complex projects the restraints are so severe that few, if any, completely satisfactory design solutions may be found.

It is fortunate that the projects with a greater number of solutions which are acceptable from the standpoint of usefulness are in general those for which esthetic character is highly important. Thus the broad choice of <u>useful</u> solutions for a vacation resort allows freedom for the necessary <u>esthetic</u> consideration. On the other hand, the many restraints on the construction and function of oil refinery buildings serve to limit the number of <u>useful</u> solutions, and thus the range of esthetic choice. Since oil refineries are isolated from the general public and employ only few workers, their esthetic character is not a primary concern; as it happens, the esthetic value attained in some such projects largely by accident is generally held to be pleasing by our society.

Limitations

There are four major limitations to the extent and validity of the illustrative design project of Chapter VII and the studies of Chapters IV, V, and VI. These limitations are presented in approximate order of their effect.

1. <u>Lack of Collaborators</u>. The effect of this limitation is principally apparent in the assumptions and conclusions concerning the many technical phases of power station design and operation. The writer's lack of familiarity with these fields has been partially overcome by reference to the literature and by helpful suggestions from others. However, most such choices must be considered largely as arbitrary assumptions to provide basis for architectural design.

2. Scale of Effort. The limitation here is principally one of extent. A large design group and an extended time schedule would be required for a completely developed design solution.

3. Inaccessibility of Classified Information. Only a part of the data on existing nuclear reactors and on design studies for power station reactor systems is available in the unclassified literature. Since this thesis is based entirely on unclassified information, it is limited by the amount and worth of such information. The limitation is not serious at the level of study pursued.

4. Lack of Precedent. There are no full-scale nuclear power stations completed at the present in the United States. Existing conventional steam-electric power stations, conceptual designs for nuclear stations, and research facilities offer basis for some parts of a nuclear station design.

Objectives

The three principal objectives of this thesis project are:

1. Formulation of methods for the design of industrial architecture.

2. Analysis of the major planning and design problems of nuclear power stations.

3. Development of an illustrative design for a nuclear power station.

CHAPTER II

POWER STATIONS AND NUCLEAR REACTORS

Electric System Characteristics

The early electric power systems were small one-station radial feeder arrangements with all loads located quite near the generating station. This was necessary because these stations generated direct-current power at low voltage for direct use. With the introduction of alternating current generating equipment and transformers the small local stations were abandoned in favor of larger, central-station generating plants which fed into extensive distribution systems either directly or through high voltage transmission lines. Since this pattern of central-station alternating-current generation is almost universally used in the United States at the present time, all further discussion will be confined to such a system.

Components

The typical electric power system consists of the following component activities:

Production (generation)

Transmission

Distribution

Business activities (sales, accounting, advertising)

Management

These various activities enter into the operations of the system to varying extent in different areas. Thus, a large <u>wholesale</u> supplier of electric power in a sparsely settled region (such as the Bonneville Power Administration in the Pacific Northwest) will be mainly concerned with production and transmission, while a small utility company in a city may actually buy its power from other systems, and is principally concerned with distribution and business activities.

The present study will consider principally production of power; transmission will be considered to the extent that it is a significant factor in site selection. The remaining operations will not be considered, on the hypothesis that they are existing parts of an established system to which our proposed plant is an addition.

<u>Operation of a System</u>

Due to the many uses to which electric power is diverted, and the regular cyclical nature of most of these uses, the demand is susceptible to fairly reliable prediction. This demand is not generally constant, however, but exhibits sharp peaks and depressions on daily, weekly, and seasonal bases. One of the foremost problems of system operation is that of scheduling sufficient generating capacity for peak demand without maintaining an excessive operating reserve. A coupled problem is that of determining capacity requirements to allow for scheduled and emergency maintenance of generating equipment.

The problem of scheduling for peak loads generally is resolved by programming the more efficient plants or generating units of a system for <u>base-load</u> operation; that is, for essentially continuous operation at a constant load. The less efficient (probably older) units of the system are then utilized for supplying the additional energy requirements for peak demand. (Other complications such as the dependability of water supply for hydro-electric generating units are involved, but these are beyond the scope of the present work.)

The problem of frequency control is an important one in the alternating-current system for several reasons. The frequency of the electric current is a function of the speed of revolution of the generator and its prime-mover. As the load on a generator changes, its speed tends to change, and must be governed if frequency is to remain constant. This constant frequency is necessary if power is to be supplied from several generating units to a common transmission or distribution system. The control is also necessary to regulate the speed of motors and electric clocks.

The problem of providing sufficient capacity for peak demand has led to the interconnection of systems for combined operation. Thus, the capacity of any unit in the system can be called upon, as needed. This increases reliability and allows reduction of the ratio of total capacity to operating capacity, with attendant reductions in capital investment and operating costs. Interconnections are of various operational types, some being called upon to deliver a constant load from supplying utility to distributing utility, while others are called upon only to balance peak demands or to facilitate scheduling of outages. As the economic size of generating stations increases, system interconnections become of increasing importance. The large blocks of power produced efficiently by newer large central stations can be used to supply the base load of an entire interconnected system, while the less efficient plants of the various component systems contribute to peak load operation, reserve capacity, and frequency control.

Generating Stations

Energy Sources

The electric generating equipment in common use today requires that mechanical energy be produced to turn the shaft of the rotary generator. The methods of producing this mechanical energy which are feasible for use at this time are three in number: the utilization of the kinetic energy of falling water, the utilization of heat produced by chemical reaction, and use of the heat produced in a nuclear reaction. The first method is a direct translation of the kinetic (mechanical) energy from the moving water to the rotating turbine impeller. The second method utilizes the heat from burning of fuels such as coal, oil, and natural gas to produce steam for steam turbines; uses fuels such as gasoline and diesel oil in internal combustion engines; or uses natural gas directly in gas turbines. The third method, not in common use yet, is that of generating steam for turbines with the by-product heat produced from controlled fission of unstable elements in a nuclear reactor.

Prime Movers

Since the generation of power with hydro-turbines involves the translation of the kinetic energy of falling water, it is dependent on the velocity of the water and thus on the height of fall. For this reason, hydro-electric plants are most efficient when connected with storage facilities in the form of dams, which give relatively great water level differentials. Run-of-the-river hydro-electric plants are not only less efficient because of small level differentials, but also suffer from the variability of stream flows. These run-of-the-river plants are commonly small compared to storage-dam plants. In some parts of the United States, notably the Pacific Northwest, hydro-electric plants account for the largest share of power production. In New England, however, they are principally used for peak loading. This is partly due to the lack of large swift rivers such as found in the Northwest, and partly occasioned by the early development of the available hydro sites with small, now obsolescent, plants. When additional power was needed, it was expedient to develop steam-electric plants rather than to replace the hydro-electric plants.

The principal means of power generation in the United States at the present time is by steam-electric cycles. About four-fifths of the electric power of New England, and a somewhat smaller proportion of the total U.S. production, is produced in this manner. The predominant fuel for use in steam boilers is coal, but significant amounts of oil and natural gas are used. Great advances have been made in the operation efficiency of steam-cycle plants in the past few decades. Principal improvements have been the increases in steam temperature and pressure, use of regenerative feedwater heating, and use of reheat cycles. Steam temperatures in the newer plants range up to 1100 degrees F. and higher, while pressures of 1200 psig are common and pressures up to 4500 psig are used. These increases of temperature and pressure affect the reliability and initial cost of boiler and turbine assemblies and such effects must be weighed against the savings in fuel consumption to determine actual usefulness. The operation of regenerative feedwater heating is that of extracting uncondensed steam out of the turbine after it has passed through the first stages, and using this steam to preheat water for the boilers. Often several stages of heating are used. Reheat cycles are arranged by taking the steam out of the turbine part way through, and returning it to the boiler system for reheating before introducing it into the next stages of the turbine.

Gas turbines and internal combustion engines are not widely used for public utility electric power production, their use being mainly restricted to industrial power generation, mobile or emergency units, and certain special locations with abundant cheap fuels. They are not generally competitive with steam-cycle central stations.

Condensing Systems

Because the overall efficiency of a steam-electric generating station is low, a great deal of importance is attached to the circulating water system which carries away the largest part of the waste heat. (In a conventional fuel-fired boiler, the stack gases also carry out some heat.)

The steam, which is introduced to the turbine at high temperature and pressure, expands and cools on its trip through the turbine stages. The efficiency of the turbine cycle depends on the differential that can be obtained between inlet and outlet conditions, and thus on the outlet temperature and pressure conditions. Most modern turbines exhaust into condenser units which serve to condense the steam at a very low pressure (usually 1 to 2 inches of mercury). The partial vacuum maintained helps to pull the steam through the turbine and lowers the condensing temperature. The condensate is then pumped back through feedwater heaters and eventually returns to the main boilers to be cycled again.

The condensers used with modern turbines are of the surface condensing type which pass the steam past banks of tubes carrying circulating cooling water. By the use of this type rather than a mixing type condenser, the condensate is kept in a closed system and is not contaminated by the circulating coolant. Since the steam condensate is usually treated water, this isolation is necessary for economy. There are several common ways of handling the circulating water, as explained below.

1. Once-through Circulation. Cold fresh water from a river or pond, or salt water from the sea, is pumped through the condenser tubes and wasted back to its source, usually far enough removed from the inlet to minimize mixing and recirculation. This type of installation is commonly used where large quantities of water are available. Its great advantage is in the small amount of preparation or work expended on the circulating coolant. Sometimes gravity flow is utilized to eliminate pumping. The disadvantages of once-through cooling are that it requires constant screening to remove floating contaminants, that it carries large quantities of impurities into the condenser tubes, and that it requires large quantities of water. The condensers for a 50,000 kw turbine-generator will require from 20,000 to 60,000 gallons per minute of circulating water. Thus it is seen that a once-through system can only be located at a river, ocean side, or large pond or lake.

2. Recirculating Systems. The systems of this type recirculate most of their cooling water between the condensers and a cooling facility. The common cooling facilities are spray ponds and cooling towers. Spray ponds are arranged with piping and nozzles which spray the hot water into the air a few feet above the pond surface. Cooling is mainly by evaporation of the falling spray. The losses by evaporation and wind are substantial, thus requiring a make-up water source. The cooling tower system operates by pumping the hot water to the top of towers and letting it flow (drip) down through slats and

and baffles which break up the flow into drops and allow efficient evaporative cooling. Air flow in the tower can be either natural or mechanical draft. The losses from wind are not so high as those from spray ponds, but construction costs and operating costs are somewhat higher. Cooling tower installations do not require as much land as spray ponds.

Once-through cooling systems in modern steam-electric stations usually employ single-pass condensers in which the cooling water enters at one water box, traverses the tube length, and is wasted from the water box at the other end. Such condensers offer minimum flow resistance. Recirculating type systems commonly employ two-pass condensers in which the cooling water enters at the bottom of the water box at one end, traverses through the tubes and back, and is wasted from the top of the same water box. These condensers offer greater flow resistance, but high pumping head is required anyway for a spray pond or cooling tower. According to one writer, single-pass condensers require about 50 per cent more circulating water than two-pass types, but are only about 80 per cent as large as two-pass types in physical dimensions.[1]

Generating Equipment, Switchgear and Control

The generating equipment of the usual turbine-generator combination consists of a single shaft unit of main generator and exciter. The generator is usually direct-coupled

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[1]W. E. Ellingen. Selecting steam surface condensers. Allis-Chalmers electrical review. 4th quarter 1954.

to the turbine shaft. Older generators were commonly 1800 rpm machines, while the newer ones are 3600 rpm. Small generator units are air-cooled; modern units of sizes larger than about 10,000 kw are commonly cooled by hydrogen. The closed-circuit hydrogen cooling system offers the advantages of decreased windage losses (the system is sealed from the atmosphere and commonly operates at less than atmospheric pressure) and longer insulation life due to the freedom from dust and excessive temperature changes. The hydrogen coolant gives up its heat through heat exchangers to circulating water. The majority of installed turbine-generator units are probably in the size range 50,000 to 80,000 kw; newer units range up to 165,000 kw, 200,000 kw, and even beyond. The larger turbine-generator units are only available for use with high pressure superheated steam, and reheat cycles; fabrication difficulties and material properties limit the physical size of the machines, and the increased capacities are largely due to efficiency increases. The turbine-generator units to be used in early nuclear-electric plants will probably be units smaller than 100,000 kw, due to the relatively low steam temperature and pressure conditions to be expected with the early plants.

The switchyard associated with a generating station ordinarily has the combined task of transforming the electric power from the generating voltage of about 14 kv. (14,000 volts) to the transmission voltages (ranging from 23 kv. to 250 kv.) and of providing the necessary switching and protection for the circuits. The main switchgear and the transformers are generally installed outside and arranged with overhead bus connections. The electrical control room contains banks of control panels which record, indicate, and control the functioning of main switchgear and of necessary auxiliaries. The auxiliaries of the power station are many and complex. Normal operating power must be made available to operate the equipment such as pumps, conveyors, and motor-operated switches of the station. There must be power connections for operation of these auxiliaries when the generators are off the line, such as during the period of start-up. Finally, emergency circuits for operation of some systems in the event of system power failure are needed. Efficient and complex communication circuits are necessary both within the generating station and between different stations of the system in order to maintain continuity of operation. Wired telephone systems, carrier-current systems which transmit signals along the main transmission lines, and radio systems are all used.

The Substitution of Nuclear Energy for Other Fuels

The Demand for Electric Power

The people of the United States, although comprising less than 7 per cent of the world's population, produce and use more than 40 per cent of the world's electrical power. A new record of electric power production is established nearly every year. Reports of the Federal Power Commission show that production has about doubled every ten years since 1920. The report of the Paley Committee used by the AEC in their power studies predicts a demand of 1,400,000 kwh in 1975 which would require a continuation of this rate of growth.[2] In 1952 the installed generating capacity of the electric utility industry was 82.1 million kw and the total production of these utilities was nearly 400 billion kwh.[3]

The increased use of domestic electric appliances accounts for a large part of the increased demand. Improved street lighting adds to demand. The power consumption of industry is rising, due in part to the increasing mechanization of manufacturing operations. Perhaps the largest factor in increased industrial demand is the emergence of chemical and metals processing industries which require large blocks of electric energy for electrolytic processes or electric furnaces. The primary aluminum industry, as an example, is largely power oriented in location. The production of aluminum from alumina is an electrolytic process and requires nearly 10 kwh of electric energy per pound of aluminum produced. The manufacture of electric furnace steels is an expanding use of electric power. The phosphate (fertilizers) industry is another which is dependent on large amounts of electric power. A further demand for electric power is possible for conversion of sea water and the brackish water so common in the Southwest and Great Plains region. Studies sponsored by the United States Department of the Interior show great promise, although

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[2] 16th semiannual report. AEC. 121-37.

[3] M. J. Steinberg in Electric system operation. (1954), chap. 6. (B. G. A. Skrotzki, ed.).

economic processes are not yet developed.[4]

Although no other country enjoys the extent of electrification found in the United States, there is a steady increase of demand in industrialized or industrializing countries. The demand for electric power in Britain rose 50 per cent between 1940 and 1952, and another 45 per cent increase is expected by 1960.[5]

Future demand can be forecast with fair accuracy, barring war, depression or other economic disaster. A study of the New England power market, completed in 1949, predicts that the five-state region (Maine was not included because a statutory restriction prohibiting transfer of electric energy across state lines eliminates it from power pool systems) will require new capacity addition (including replacement for retired units) of the same order (4,000,000 kw) as the total installed plant in 1947.[6] The New England region is a high power cost area as compared with much of the United States, and is not undergoing such large-scale industrial development as the newer sections. For these reasons the increases are smaller than the potential increases of other regions. Thus it is seen that great expansion of our electric power systems is a reasonable certainty.

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[4]Alfred Steinberg. The sea may end our water shortage. Nations business. 74-7, July 1955.

[5]Sir John Cockcroft. British view of nuclear power. Nucleonics. 16-23, Jan. 1952.

[6]Power market survey. FPC. P-20, Aug. 1949.

Hydro-electric Power Potential

Judging from the current and predicted future increases in rate of electric power production, consideration must be given to the energy resources which are available for power production. Hydro-electric sites remain as a large potential source in many sections of the United States and of the world. In more fully developed areas such as the five-state New England region discussed previously, many hydro-electric sites were developed early, and the maximum utilization of these sites would require extensive removal and reconstruction. It has been estimated that this region had an undeveloped hydro-electric power potential of 1,300,000 kw, as against hydro-electric installations of 800,000 kw, in 1947.[7] Due to the nature and size of the rivers and streams, however, the hydro-electric power potential is limited by comparatively small sites and by intermittent or variable stream flows. For this reason, the bulk of electric power in this area will continue to be produced by steam-electric plants. Other areas, notably the Northwest with its large undeveloped hydro-electric sites, have more favorable conditions for hydro-electric production. Developments of entire regions such as the Tennessee Valley Authority successfully combine hydro-electric facilities with navigation, flood control, and other benefits. Hydro-electric power, when reliable, is cheaper than fuel-generated power; hence those areas with abundant hydro-electric resources have

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[7]Ibid.

seen the most rapid growth in power consumption, including the growth of power-oriented industries.

Chemical Fuel Energy Resources

Studies have been made for the AEC by Putnam on the availability and rate of exhaustion of the earth's energy resources.[8] An amount of energy referred to as Q, and equal to 1×10^{18} Btu, was used as a unit. Putnam estimated that prior to 1860 (including 100 years of the industrial revolution) only about 7 Q had been consumed. Between 1860 and 1947, about 5 Q had been consumed and the rate of use was increasing so rapidly that it was estimated that by the year 2000 30 Q will have been consumed. The rate of consumption in 1947 was estimated at 0.1 Q per year, and the predicted rate of consumption for the year 2000 is 1.0 Q. The total known reserves of gas and oil were estimated as 0.4 Q, and the total known reserves of coal as 68 Q, with about 6 Q considered as being economically feasible to recover at the present time. Thus it can be seen that our presently used energy resources are limited. The use of coal and petroleum as raw materials for various synthetic products (e.g., nylon) imposes a further limitation on available energy supplies. As the reserves of these sources dwindle, their cost will tend to increase due to increased difficulties of extraction.

Energy from Nuclear Fission

The utilization of nuclear energy is thus a necessary

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[8]This material is quoted from K. H. Kingdon. Progress report on nuclear power. Nucleonics. 18-23, April 1952.

development, if we are not to restrict the trend of industrial growth and increased energy consumption. The energy reserve from naturally occurring nuclear fission energy sources alone is estimated as 12 Q, and as nearly 1800 Q including use of breeding and conversion cycles.[9] The energy from known fissionable materials is seen to be an important reserve, when compared with supplies of other sources.

The possibilities of utilizing the energy from fissionable materials are important from another aspect. When compared to conventional fuels, the fissionable source can be considered as a <u>weightless</u> fuel, as its potential energy release is 3,000,000 times that of coal, for equal weight.[10] The advantages of a weightless, low volume fuel in terms of transportation costs are important considerations in a power station design. In addition, this property makes its use in a mobile or portable power unit desirable. Necessary shielding and constructional requirements largely offset this advantage, but a successful submarine power plant, the Nautilus, is already in operation. A portable electric power plant is being developed, and aircraft, train and ship propulsion units are being studied.

The utilization of nuclear energy entails some rather severe complications. The heat produced in the fission process

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[9]An important milestone. Nucleonics. 8, July 1953.

[10]C. G. Suits. Power from the atom -- an appraisal. Nucleonics. 3-12, Feb. 1951.

is accompanied by powerful radiations, and the products of the fission process are in themselves highly radioactive. Such radiations are lethal, and careful shielding and contamination control is necessary. The reactors used for power production would be capable of producing materials for nuclear weapons, hence political and governmental control implications are present.

Other Possible Energy Resources

Solar energy appears to be a possible source of terrestrial power, but at present there are few instances of success in harnessing it for economic use.

The possibility of harnessing the nuclear fusion reaction to produce useful power is intriguing. The AEC has announced that work is in progress on such a task.[11] Scientists apparently believe that the odds of success are small, but the benefits would be great, since the source materials are much more abundant than those of the fission process.

Nuclear Reactors

Description and Background

A nuclear reactor can be defined as an apparatus in which nuclear fission may be sustained in a self-supporting chain reaction. The basis for development of nuclear reactors was the discovery, by Fermi, that an atomic nucleus of

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[11] Long-range plan to tame H-bomb revealed by United States. New York times. Aug. 12, 1955.

uranium 235 when struck by a free neutron would sometimes split into several parts which were the nuclei of lighter elements, and would emit neutrons, other particles, and radiations. This process of nuclear fission, when properly controlled, becomes the chain reaction of the nuclear reactor. The chain reaction is possible because of the neutrons released in the fission. These neutrons can be absorbed in the nucleus without causing fission, however, and can be absorbed by other elements in their path. In addition, they can be slowed by collisions not resulting in absorption. This slowing has importance since the velocity of the neutrons emitted in fission is considerably higher than that of most probable capture resulting in fission. It is desirable to slow the neutrons to thermal velocities in a moderator material and make them available for capture resulting in fission. Since there are, on the average, about two and a half neutrons released per fission,[12] and one neutron per fission must produce fission in another nucleus to maintain the chain reaction, neutron economy is a very important consideration in reactor design.

Figure 1 is a diagram of expected neutron economy in a particular reactor.[13] Since this reactor, the Canadian NRX, is used for research and production of radioisotopes, the exact economy varies from that to be expected in a reactor operated

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[12]John D. Trimmer in Nuclear reactors for industry and universities. (1954), chap. 2.

[13]F. W. Gilbert. Canadian facilities for isotope production and bombardment. Nucleonics. 6-8, Jan. 1952.

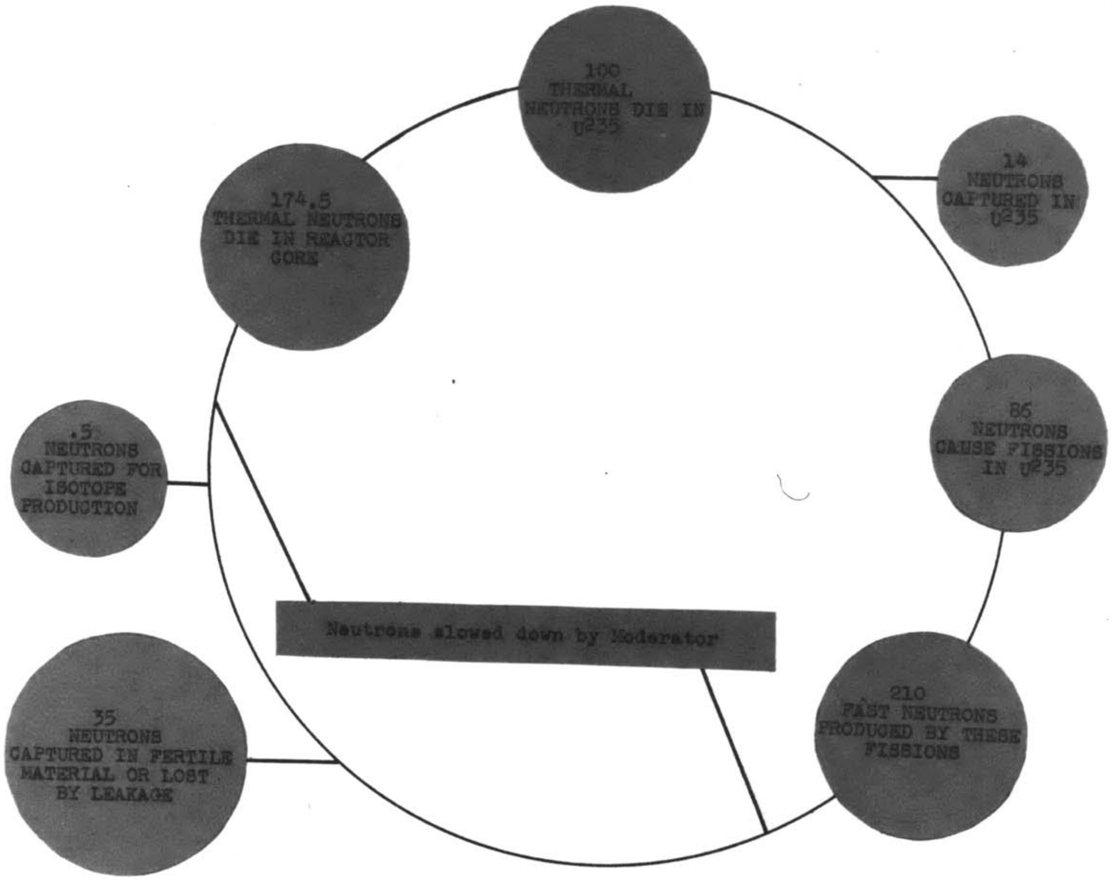

ILLUSTRATION OF EXPECTED NEUTRON ECONOMY IN CANADIAN NRX REACTOR (13)

Figure 1

for heat production, but the processes are similar. The heat output of a fission is estimated as 80 per cent of the total energy liberated; the remaining 20 per cent is expended as radioactivity or otherwise lost.[14]

Subsequent to the discovery of the fission process it was found that transmutation of elements was possible. By bombarding atoms of so-called fertile isotopes, uranium 238 and thorium 232, with neutrons they could be changed into the unstable isotopes plutonium 239 and uranium 233, respectively. Thus the stable isotopes of elements occurring naturally in the earth's crust could be transmuted into synthetic unstable elements which were fissionable in the same manner as naturally occurring uranium 235. This is the process known as conversion. The process of conversion is important to any discussion of nuclear power, as it provides a means for extending the reserves of fissionable material in the earth. A reactor which can produce new fissionable materials by transmutation at a rate greater than that of its burn-up of fissionable material is a special case of the converter, and is known as a breeder reactor. This type deserves special attention due to the great increase in available fissionable material which it makes possible. Although uranium and thorium are available in the earth's crust in appreciable quantities there is no fissionable isotope of thorium and the unstable isotope

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[14] L. A. Ohlinger. Engineering aspects of nuclear reactors. Nucleonics. 38-49, Dec. 1949.

of uranium, U-235, is present as only 0.7 per cent of all natural uranium. Only by conversion or breeding can these resources be fully utilized.

The development of nuclear reactors was begun during the second world war. The Manhattan District of the Corps of Engineers was responsible for the work, although most was done by civilians, including many of the foremost scientists of this and other countries. Due largely to this beginning, and to the unique importance of the United States' nuclear weapon superiority in the postwar period, much of the vast body of knowledge about nuclear processes and technology has remained under security classification. However, in the last several years, the advisability of creation of a broad base of industrial knowledge and use of nuclear processes has resulted in an increased availability of information. The facilities built during the wartime emergency were necessarily developed for production rather than for research. Much of the construction was a calculated gamble, that of building full-scale facilities without prior construction and operation of pilot plants. With the establishment of the Atomic Energy Commission in 1946 as a permanent peacetime civilian agency for the continuance of nuclear investigations and materials production, more emphasis has been placed on basic research and coordinated programs of development.

Analysis of Design Factors

The use of a reactor is a primary determinant of its characteristics. The different uses to which a reactor might be assigned can be listed as:

1. Fuel production (use of conversion or breeding to produce fissionable material);
2. Heat production (extraction of the heat produced in the fission process);
3. Production of radioisotopes and neutrons for research;
4. Reactor design and development studies.

Reactors have been designed to serve several of these assignments together.

Capture-energy classification is another basic determinant of reactor characteristics. The energy level at which the majority of neutron captures resulting in fissions take place can be classed as:

1. Fast (essentially the velocity at which escape from the fissioning nucleus takes place);
2. Intermediate (somewhat slowed from the escape velocity, by collisions with other nuclei previous to capture);
3. Slow or Thermal (slowed to thermal velocities by collisions with other nuclei before capture).

As mentioned previously, the probability of a capture resulting in fission is greatest at thermal velocities. The operation of a reactor at thermal neutron energy level thus requires a moderating material. For power production only, operation at thermal levels is attractive, as the minimum amount of fuel for chain reaction is required. The neutron captures which result in transmutations, and thus in convertor production of new fissionable material, take place at intermediate or fast neutron velocities. Therefore a reactor for conversion or breeding use does not need the extensive moderator of the thermal reactor. Because of the small probability of capture resulting in fission at intermediate or fast neutron velocities, more fissionable material is commonly required for sustained chain reaction.

The fissionable materials can be introduced into the reactor in many forms. U-235 is commonly utilized in natural uranium, that is, as the 0.7 per cent occurring with U-238 in nature. When used in this manner, the U-238 can be used as source material for the conversion process. U-235 and the synthetic materials can also be used pure or with diluents (carriers) as gases, liquids or solids.

The coolant used in a reactor has important bearing on the operation of the reactor. Coolants which are used or deemed feasible for use at this time vary widely in heat transfer characteristics and in nuclear characteristics. Since the coolant must pass through the core of a reactor to carry away the heat, its nuclear properties are particularly important, as it may act as a neutron absorber or moderator. In addition, the heat transfer and physical characteristics of the coolant are important because they determine the power level and temperature at which the reactor can operate. Since the power production from coolant energy extraction is a thermodynamic process, operation at elevated temperatures is advantageous. Together, the physical, thermal, and nuclear restrictions on coolant choice present a severe problem. The coolants which appear to satisfy these requirements for particular reactors are:[15]

Air

Helium

Ordinary water (H_2O)

Heavy water (D_2O)

Liquid metals (sodium, potassium, bismuth, lead, etc.)

The liquid metals (particularly sodium) offer great advantages since they can be used at much higher temperatures than the others. Coolant choice and temperature impose restrictions also on the coolant handling systems. Corrosion problems in particular are very difficult.

The moderator used in reactors also presents a difficult problem. Again, both physical and nuclear properties are important. Those elements with small atomic weight are the best for slowing neutrons because the average energy transfer per collision is the greatest, but most of the light elements have neutron capture cross-sections which are too high to allow their use as moderators. The best moderator is deuterium, the rare isotope of hydrogen, which forms heavy water. Carbon (in the form of graphite) and beryllium are also excellent moderators. Ordinary water is an acceptable moderator, although it has a fairly high neutron capture cross-section. The ability

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[15] O. J. Woodruff, Jr. and others. Coolants. Nucleonics. 27-34, June 1953.

of many of these materials to withstand elevated temperatures is limited, and it is likely that for reactors operating at high temperatures, fast neutron designs will predominate.

It is advantageous to place a reflector around the active core of a reactor in order to reflect straying neutrons back where they can ultimately be captured. The materials used for this service must exhibit in general the same characteristics as those used for moderators, and the same materials are commonly used.

According to Ohlinger,

> . . . to a first approximation, the amount of energy that may be released within a reactor, and hence, the amount of power that may be produced thereby, does not depend upon the size of the reactor as determined by nuclear considerations . . . the limitation on power production is dictated by the mechanical and thermodynamic ability of the engineers to remove the desired amount of power from the small volume required by the nuclear physical considerations.

He states further that "the size of the reactor may vary anywhere from a tiny sphere about one foot in diameter up to the size of a house" and can be "any simple geometrical solid in which the three principal dimensions are approximately equal."[16] The shape of the active core of a nuclear reactor and its size will depend largely on the character and configuration of fissionable and source materials, coolant, moderator and reflector. Graphite moderated reactors are commonly constructed with the graphite as the structural material in which the lattice of fissionable material and the coolant circulating

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[16] Ohlinger, op. cit.

system are held. Reactors with liquid moderators, or with liquid solutions carrying the fissionable material, generally are enclosed in cylindrical metal tanks.

The control of a nuclear reactor is a very exacting and difficult task. As was mentioned previously, the power level of a reactor is essentially independent of temperature and size. The power level is varied by controlling the number of neutrons available for capture resulting in fission. Such controls must be fast-acting and reliable if the reactor is to remain in operable order. Many new instruments and devices have been developed for reactor control, and the field of instrumentation for nuclear measurements is a fast-growing one. This control problem will add new complications to the control of power stations, as the furnace controls for conventional systems are much simpler than their nuclear reactor counterparts.

A severe problem connected with the operation of reactors is that of processing the fuel materials. There are two phases of processing of interest: preparation of material for use in the reactor, and processing, separating and purifying the products of fission and the synthetic fissionable materials created in the reactor. All reactors require the first sort of processing in one form or another. Heterogeneous reactors employing solid fuel elements usually require some sort of fuel cladding to control corrosion and contamination, while homogeneous reactors necessitate a make-up process to combine the fissionable material with its carrier. The second phase of processing, that of separation of the various products of the reactor, is subject to wide variation. A reactor operating for power production could eliminate this processing, and discharge all spent fuel materials to disposal. This would not likely result in economical operation, however, as the fission products represent potential radiation sources for research or irradiation processes, and all of the fissionable material cannot be expended in one pass through the reactor, since the fission products which are formed are neutron absorbers, which limit the chain reaction of the reactor, unless removed. For this reason, and because of the need for conservation of fuel resources, it seems probable that reactors used for power production will require processing plants as accessory facilities. Methods of separation of the converted material and the fission products that are used, most of which are common in the chemical process industries, include co-precipitation, solvent extraction, ion exchange, and volatilization.[17] Many complications of the chemistry and the radioactivity of these materials make the processing costly.

With the increasing usefulness of radioisotopes in industry and research, and with development of irradiation techniques for food and drug sterilization, it appears that chemical processing of spent fuels will be extended to include these by-product uses.

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[17]Ibid.

As a result of the relatively small amount of factual information available in the unclassified literature on operation of a nuclear reactor there have been wide variations in the estimates put forward with regard to hazards. As an aid to understanding the information available and evaluating the estimates, two distinct types of hazard can be considered.

One type of hazard is that to operation personnel and outsiders from normal operation of the nuclear reactor system. In addition to the ordinary safety hazards found in any industrial situation, there exist two hazards unique to nuclear facilities. The first is the radiation emanating from the reactor and its accessories. This hazard can be reduced to a safe level by proper shielding. The second hazard is that from contamination of air, water, or exposed surfaces by particles of radioactive materials. This hazard can be controlled by careful facility layout so as to minimize contact with contamination, by good air-conditioning and ventilation design, and by proper maintenance and housekeeping. Careful monitoring of ventilation exhaust, proper disposal procedures, regulated handling and processing of fuel materials, and monitoring of work stations are necessary to maintain adequate protection against operation hazards.[18]

Another type of hazard connected with nuclear reactor facility operation is that due to malfunction, catastrophe,

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[18] James M. Smith, Jr. Radiation safety for a reactor. Nucleonics. 41-5, June 1953.

or other emergency. It is here that the greatest difficulty in assigning risk occurs. Due to the large amounts of highly radioactive materials contained, reactors are capable of spreading contamination over wide areas under certain conditions. Containment arrangements are possible which would restrict such spread, however. Some reactor types are inherently safe; they tend to shut themselves off when control fails. Others are inherently unsafe and could conceivably run away. Reactor failures have occurred with substantial release of contaminants, but without injury to personnel, due to proper safety measures.[19] The most serious potential hazards are probably those connected not with the reactor itself, but with the handling, processing and disposal of the source and fissionable materials and the products of fission. Necessity for transporting materials and wastes in large scale on public transport involves risk, the magnitude of which will be difficult to ascertain. Permanent disposal of unusable radioactive wastes poses another problem on which much work remains to be done.[20]

These hazards will probably serve to keep nuclear reactors out of the most congested areas, at least for the present. However, it should be noted that these are not the only hazards to our urban existence. Petroleum refineries and

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[19] F. W. Gilbert. Decontamination of Canadian reactor. Chem. eng. progress. 267-71, May 1954.

[20] 17th semiannual report. AEC. 30.

gasoline tank trucks pose everyday hazards which we have learned to forget. Even conventional steam-electric stations can be dangerous. Several large modern steam turbines have blown up in recent years, with loss of lives.[21]

<u>Present Stage of Development and Application</u>

Large reactors have so far been built primarily to supply materials for nuclear weapons. Little information on these is available because of security limitations. They are, however, an important source of information for the design of reactors for peaceful uses of nuclear energy.

Research and development reactors have been built principally in small power output designs, but are important to the design of power reactors for two reasons: there is more information available outside of security restriction, and there have been more types and systems developed on experimental scale than in full-scale production reactors. Two very important developments to the future of nuclear power have been the successful operation of a "breeder" reactor[22] and the generation of electric power by a reactor system.[23] Both were accomplished by research scale programs of the AEC.

The past several years have been a period of great effort and interest in application of nuclear energy resources

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[21]Commonwealth's Ridgeland no. 4 turbine explodes. Power engineering. 78-9, Jan. 1955.

[22]Breeding successful. Nucleonics. 87, June 1953.

[23]EBR. Nucleonics. 72, Feb. 1952.

to the generation of electric power. Many countries of the world are participating in attempts to apply nuclear power to electric generation and to propulsion. The government of Britain has made significant progress and has announced a ten-year program of design and construction of nuclear reactor-electric power stations.

In the United States, the AEC has actively guided and financed a program of research, which has been accelerated since 1952 by studies of power reactor systems by groups of industrial concerns.[24] These studies, done under AEC guidance and help, assisted in paving the way for the five-year program of power-reactor development announced by the AEC in 1954.[25] This program was designed to include research and development on those types of systems which promised reasonable chance of success within the five-year period. Of the five systems chosen for development, one, a pressurized-water thermal reactor, will be a full-scale operating plant. The others are pilot-plant units for development of less-well-known systems, and include a boiling water reactor, a sodium graphite reactor, a fast breeder reactor, and a homogeneous reactor. In addition, the AEC has been involved in development and design work on mobile power units, of which one, the submarine Nautilus power plant, is already in service. As a further attempt to spur development of small-scale power reactor units, the AEC

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[24] Nuclear power reactor technology. AEC. (1953), vol. 1. Also Nuclear power reactors. AEC. (1955), vol. 2.

[25] 17th semiannual report. AEC. (1954), 21.

and the U.S. Army have contracted for a portable nuclear reactor generating station, suitable for isolated military outposts. This unit would not be expected to produce electric power at costs competitive with central-station power, but its use of low weight, low volume, long life fuel would be an important advantage.

As a result of the revisions of AEC legislation in 1954, increased participation in development of nuclear power has been offered to private industry. One important result was the invitation the AEC extended to private utility groups to propose designs for central-station power plants to be built for their systems, with AEC help. There were five offers filed with AEC before the April 1955 deadline.[26] The most significant offer was that of Consolidated Edison Company of New York, which proposes to build a large plant on the Hudson River above New York City entirely with its own funds.[27] The station as proposed would consist of a pressurized water reactor which would produce steam in a heat exchanger system. This steam would be superheated in an oil-fired superheater boiler, and fed to turbine-generators. Of the 236,000 kw rated capacity of the station, 140,000 kw would be developed by the nuclear reactor system, with the superheater accounting for the remainder. This combination system allows the use of

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[26] Nucleonics. April 1955.

[27] Consolidated Edison to build nuclear plant. Power engineering. 91, May 1955.

modern high temperature and pressure turbine units, at the increased efficiency they offer.

The offer proposed by Commonwealth Edison Company of Illinois, along with its associates, is of an interesting system. The plant proposed, entirely nuclear energy, would eliminate an intermediate heat exchanger system, passing the reactor coolant (boiling water) directly through the turbine as steam. The entire main plant, consisting of reactor, turbines and generators, would be enclosed in a closed shell to prohibit the escape of contaminants.

While none of the systems proposed to date is expected to be competitive costwise with the best of present-day fuel-burning plants, they are expected to match or pass the production costs of some of the older units still in use on the respective systems.

Cost Considerations

Cost Factors in Conventional Systems

The total costs of power facilities can be expressed in various ways depending on the point of attack. As mentioned earlier, the electrical system consists of several parts, of which the production plant is the first and the transmission plant the second. We shall here confine our discussion to the costs of production. The most meaningful index for our discussion is that of unit cost of electric power, expressed in tenths of a cent (mills) per kilowatt hour (kwh) of electric energy.

Costs can be divided into two parts; the first part pertains to the initial investment in the plant, and the second is concerned with the operation of the plant. The classification shown by Skrotzki is:[28]

1. Fixed charges

   a) Interest (return on investment)
   b) Taxes
   c) Depreciation costs
   d) Insurance costs

2. Operating expenses

   a) Operating supervision and engineering
   b) Operating labor
   c) Fuel costs
   d) Supplies
   e) Water
   f) Maintenance
   g) Miscellaneous expenses

The fixed charges for the system as a whole range from 8 to 21 per cent of total costs according to Skrotzki, while fixed charge costs for the production plant (generation) are commonly about 12½ per cent of total production costs.

Considering the components of fixed charge costs, those of taxes and insurance are more closely related to financial than to technical considerations, and will not be discussed here. The matter of depreciation is of considerable importance, however, as a determinant of cost which is technologically governed. A study of depreciation practices in the electric utilities[29] has shown that most utility companies use a

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[28] M. J. Steinberg, op. cit., chap. 8. (Skrotzki, ed.)

[29] Electric power statistics, report no. 54-11C. FPC.

straight-line method of figuring depreciation; that is, they depreciate their physical plant by a fixed amount for each year of its anticipated life. The anticipated life varies with type of plant. Values averaged for many companies indicate expected life as follows:

69 years . . . Hydro plants
40 years . . . Steam plants
40 years . . . Transmission facilities
35 years . . . Distribution facilities
27 years . . . Internal combustion engine plants
23 years . . . General

This would indicate that the depreciation costs per kwh of electric energy should be substantially less for hydro-generated power than for steam-generated power. Although the interest rates for investment return are matters of financial concern, the amount of investment is related to the type of plant. A representative figure for investment in conventional steam-electric central stations might be $190/kw, while a comparable figure for investment in hydro-electric stations would be perhaps $300/kw. Thus the interest component of fixed charge costs per kwh of electric energy will in general be higher for hydro power than for steam power.

The following analysis of the construction costs of steam-electric stations will be helpful in determining the apportionment of costs of the total plant. Data have been obtained from a report of a survey by Electrical World magazine.[30]

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[30] Steam power plant costs drop. Engineering news-record. 151-5, Oct. 8, 1953.

The data are for construction costs of the years 1948 to 1951 per kw of rated station capacity.

These costs can be translated into terms of June 1955 costs by use of Engineering News-Record Building Cost Index.[31] Based on the assumption that construction and purchase of equipment for these plants was spread uniformly over the four-year period, 1948 through 1951, the equivalent June 1955 costs are:

	Adjusted Cost $/kilowatt
Total station	$190
Structures and improvements only.	45
Boiler plant equipment only	74
Turbine-generator equipment only.	50
Other	21

In addition to costs, the Electrical World study provided data on station space allocations. Averages for the 11 stations in terms of volume in cubic feet per kw are:

	Cubic Feet/kilowatt
Boiler housing.	12.9
Turbine-generator housing	9.9
Office and employee facilities.	1.3
TOTAL -- major spaces.	24.1

Based on cost data of the TVA Watts Bar steam station,[32] a typical steam-electric station of medium size (240,000 kw) constructed in 1940-46, the major spaces tabulated above are

[31] Construction costs: 1952-53. Engineering news-record. Oct. 8, 1953. Also Construction costs: 1953-54. Engineering news-record. Oct. 7, 1954. Also Engineering news-record. June 23, 1955.

[32] The Watts Bar steam plant. TVA. (1949), 237-56.

estimated to account for 80 per cent of structures and improvement costs. Thus, the 24.1 cubic feet per kw should cost (0.8)(45) = \$36 or \$1.50 per cubic foot.

Considering the components of operating costs, those which are subject to large differences between types of plant are fuel costs, supplies, and water costs. An estimate of fuel unit costs shows them to be 60 to 80 per cent of operating costs for conventional steam-electric stations.[33] Supplies are usually a larger item of cost for steam stations than for hydro stations due to the necessity for water treatment. Water costs, on the other hand, will vary greatly with either type of station, being dependent on location. In general, the operating costs of a hydro-electric station will be lower than those of a steam-electric station by a considerable margin, since fuel costs predominate for the steam station. Thus the overall costs of hydro-electric power can be expected to be below those of steam power.

Cost Factors Governing Substitution of Nuclear Plants

Most writers on nuclear power prospects have agreed that present costs would fall above those of modern steam-electric stations. There is wide variation, however, beyond this agreement. A thorough discussion of the costs of nuclear-electric power is beyond the scope of this work;[34] however, it

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[33] M. J. Steinberg, op. cit., chap. 6. (Skrotzki, ed.)

[34] A thorough discussion of the economics of nuclear power is found in W. Isard and V. Whitney. Atomic power. (1952). See also Nuclear power reactors. AEC. (1955), vol. 2.

will be helpful to point out a few of the major differences between nuclear and conventional steam-electric power costs.

Considering fixed charge costs, there are important differences between fuel-burning and nuclear situations. First, the investment in a nuclear-electric station is at the present time bound to be greater than that in a steam station. The essential difference, as explained earlier, lies in the substitution of a nuclear reactor for the conventional fuel-burning boiler heating unit. The cost differential is due to complexity, control difficulties, need for safeguards, and precision of construction of the reactor. Various estimates are available, but perhaps the most recent is a comparison of the estimated capital cost of the Consolidated Edison Company project of $230/kw[35] to the figure of $190/kw quoted above for conventional steam plants. This increase in capital investment, possibly accompanied by an increase in interest rates due to the financial risk of untried systems, results in an increase in fixed charge costs. Secondly, the depreciation costs of the conventional steam station are usually based, as mentioned earlier, on a life approaching 40 years. It is unreasonable to use such estimates for nuclear stations, since the history of nuclear reactors only extends back for about ten years, since many features of a power reactor will be essentially untried, and since technological improvements will hasten obsolescence. Anticipated life estimates of five to

[35]Consolidated Edison to build nuclear plant. Power engineering. 91, May 1955.

20 years are common in published economic studies, hence depreciation costs will be greater than for steam stations. Insurance costs are uncertain, as no quotations are yet available on which to base costs. These are certain to be above costs for conventional stations because of the new hazards involved and the lack of experience in operation of such systems. Thus it would appear that fixed charge costs of nuclear stations will greatly exceed those of conventional stations in the foreseeable future, and probably will remain higher indefinitely.

Considering operating costs, however, the situation looks brighter for nuclear stations. As discussed earlier, the fuel costs of a conventional station are the predominant part of operating costs. A large part of these costs is attributable to transportation and handling of the fuel. With the tremendous savings in bulk and weight of nuclear fuels, even allowing for increased difficulty of handling due to radioactivity, it is apparent that opportunities for savings exist. Again, there are many and conflicting estimates on the cost of nuclear fuels. To a large extent this is attributable to the fact that at present all nuclear fuels are government-owned and are under security classification. Some writers have assumed that the fuel costs of a nuclear power station can be neglected entirely, being offset by credit for the fissionable material or fission products created in the reactor. Such an assumption places the nuclear plant in a position similar to the hydro-electric plant, as regards operating costs. Certainly the increasing interest in radio-isotopes and irradiation processes[36] and the possibility of a market for converted and processed fuel for mobile nuclear power units will help to establish an economic basis for nuclear-electric central stations.

[36] Radiation, heat used to weld plywood solidly. New York times. May 29, 1955. An interview statement on possibilities of irradiation of building materials by structural engineer Paul Weidlinger.

CHAPTER III

OPERATIONS RESEARCH AND DESIGN

A Study of Method

> Architects who undertake the design of power plants are confronted with considerable differences in many respects from those customarily associated with the general practice of architecture, wherein the architect conceives the project from start to finish.[1]

This statement by an architect of power plants expresses well the altered responsibilities attending the architectural solution of industrial problems. The essential problem is cooperation between two design professions.

Architecture and Engineering

The complexity and scope of functional requirements and the high level of technological development of materials and construction combine to require increasing application of engineering in the design of building facilities, particularly those of an industrial nature. The architect of times past was inclined to consider his engineer colleagues as technicians who attended to the tedious details of heating or structural support. Today's architect is more aware of the economic and technological demands of his practice, and acknowledges the creative and analytic skills of the engineering disciplines.

In the practice of architecture, and of the engineering

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[1]Walter W. Wefferling. The power plant architect. Combustion. 53, Jan. 1952.

disciplines concerned with construction, a practical outlook is unavoidable; the emphasis is placed on application and results, and hence often on an empirical rather than a theoretical basis. In dealing with design problems having many variable factors it has often been necessary to fix these factors one at a time, with the assumption implicit that no important interrelations between variables existed. Such piecemeal methods require great experience for satisfactory results, are slow and tedious for large problems, and do not insure that the best possible answers are reached, even after several trials. Recent advances, particularly in applied mathematics, have made possible methods of more exact solution of these problems than those of the trial and error approach. To ascertain their worth to the design professions, a study of a field of application of these methods is now in order.

Definition of Operations Research

Operations Research is, most simply, research into operations -- the study of men and/or machines at an assigned task.[2] As the word "research" would indicate, it is a scientific method, a combination of quantitative hypothesis, observation, and controlled experiment. The aim of operations research (OR) is to study systems and operations susceptible to quantitative analysis (i.e., those which are repetitive, systematic, or otherwise predictable) with the purpose of

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[2]The principal source for this treatment of the nature of OR is P. M. Morse and G. E. Kimball. Methods of operations research. (1951).

understanding them. On the basis of this understanding, recommendations can be made for modification or control of the operation. OR is not a substitute for executive judgment and decision. Rather, it is a means of providing a quantitative basis for the tangible aspects of an executive decision. OR is commonly carried on by a team, as this has proven to be the best way of providing the range of knowledge and viewpoint necessary for objective analysis. The earliest OR teams, those which functioned in the various services during World War II, contributed greatly to the success of Allied efforts. These groups provided the basis for the present status of OR.

Possible Relationship to Architecture

Is there any relationship between OR and architecture? There are many large areas of interest and approach common between the two fields. One such area is type of interest. OR is concerned with the understanding of systematic or predictable operations. Architecture, wherever concerned with industrial operations, traffic, or groups of people, is concerned with housing such systematic or predictable operations and thus must be concerned with the operations themselves. OR is concerned with quantitative analysis of past events as an aid to prediction of future events. Architecture is concerned also with the past as a prediction tool. Most analysis of the past in architecture has been qualitative rather than quantitative, but the increasing involvement of science and technology in construction and the increasing severity of economic restrictions is making quantitative evaluation ever more valuable. Examples of this type of analysis can be found in construction cost studies, in earthquake damage studies, and in urban pattern studies.

The architect commonly is involved at several levels of activity in the course of his work. He is concerned at the engineering level when engaged in detail design of building construction. When engaged in basic planning and overall design, or when concerned with the organization of design activities, however, he is at the operations level. It is at this level that OR and architecture are related most closely and that possible fruitful cooperation is possible. As stated earlier, the OR function is normally advisory, not executive. The architect, on the other hand, operates in both capacities. His traditional role is that of executive, responsible for building design. With the increases in complexity of construction and building function and in specializations of efforts brought about by political, scientific, and industrial advances, the architect is becoming more and more an advisor presenting the knowledge of his field in combination with that of his colleagues from other disciplines.

The Nature of Operations Research

The Place of OR in the Sciences

OR differs from the physical sciences and the life sciences in the level of observation. Physics, chemistry, etc., are concerned at the material level and the life sciences at the level of the single being while OR is concerned at the operational level as are the social sciences. OR differs from the social sciences in that it undertakes to study all operations whether men or machines. Finally, OR is an applied science as distinguished from pure investigative science. In this sense it resembles engineering, but differs in its wider scope of study (the whole of an operation), its concentration on operations, its extensive use of the techniques of investigative science, and its emphasis on understanding rather than implementation.

Is OR a new field? Authorities in the field think so. The reasons most given are 1) its inclusiveness and 2) its direct relation to the decision-making elements of an operation. Many of the types of studies carried on by OR teams have been done under different names: time and motion studies, marketing research, industrial engineering, efficiency engineering, etc. However, these studies have usually been restricted to a particular part of an operation or enterprise whereas OR seeks to study the operation as a dynamic whole. Also, these other groups are frequently part of an engineering or research department of an enterprise while OR, when used effectively, is a staff function closely connected to the executive responsible for decisions and enjoying access to several echelons of authority. It is not intended that OR should supplant these other activities where they are properly utilized. In fact, the knowledge gained by these groups often greatly helps OR work.

The Organization and Practice of Operations Research

OR had its beginnings early in World War II. An OR group made great strides in helping to perfect the radar network which was so effective in the Battle of Britain. There were OR groups attached to all the major services of the United States and Britain during the war. After the war, the British scientists were the first to organize professionally, establishing the Operational Research Club. In the United States the National Research Council set up a committee on OR to study organization and other matters. This led to the formation of the American Society for Operations Research in 1952. This society has grown rapidly.

According to a recent study there are two principal types of OR groups in the United States[3] aside from the military groups. The first is the independent consulting firm, usually rather large. There were about eight such firms operating in 1954 of which one of the most prominent is Arthur D. Little, Inc. of Cambridge, Massachusetts. Most of these consulting firms maintain large scientific staffs and do scientific research work for industry in many fields. The other type of OR group in common existence is the group organized within an enterprise to study the operations of that enterprise. These groups are commonly permanent in nature, as contrasted to the firefighting type of service offered by the consultants. In 1954 approximately 50 companies (mostly

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[3] Student report -- Harvard graduate school of business administration. OR -- challenge to modern management. (1954), chap. 4.

industrial) had created such groups and many others had reported that they were considering similar steps. The enterprises which have set up internal OR groups have mostly been the industrial leaders; large companies which were already using some of the techniques and specialties of OR in their operations. (This is an important factor since the use of quantitative methods of analysis depends on the availability of data and criteria of operational effectiveness.) These OR groups differ from the other work forces in that they are usually attached to the company organization at the upper levels, acting as staff advisors to the decision-making executives as mentioned earlier.

Of the two types of groups, probably the permanent internal OR team is best suited to large industrial organizations which are constantly effecting production and organizational changes. The majority of companies evidently do not feel that they can afford or justify permanent groups and it is here that the field for the consultants is greatest. The consultant generally has the advantage of being able to bring more specialized disciplines and more experience to bear on a particular short-term problem due to the amount and diversity of other research in his firm.

The personnel engaged in OR work at the present time have been recruited, for the most part, from other fields of science. Since scientific method is basic to the functioning of OR, this is not an unexpected situation. Moreover, since most operations are physical systems which are studied and since mathematical techniques are so widely useful, it is only natural that physicists and mathematicians have found special fitness for and interest in this work. Of course many other disciplines are involved since one of the advantages of the OR method is that of bringing the tools, techniques, and outlooks of all interested disciplines to bear on a total problem. All writers on the subject have stressed, however, that scientific training and outlook is essential. As the Committee on OR of the National Research Council has stated,

> We believe that in this field a scientist has unique importance because he has learned that whatever his philosophical views may be, he must in his work assume the existence of a concrete external physical reality, and whatever facts or theories he encounters must relate themselves somehow in his mind to this basic reality.[4]

The range of problems which have been studied and solved by OR groups is staggering. The list would include such diverse ones as the study of movements to be followed by a large dragline equipment in strip-mining phosphate ores; study of the increased-length-of-walk versus percentage-use of pedestrian crossings over traffic arterials; programming of search operations (such as submarine search during the last war); study of location of additional plant or warehouse facilities for an enterprise; planning of agricultural crop planting; and economic studies in marketing and advertising value research. An example of OR on a large scale is furnished by the work of the Bureau of Labor Statistics which

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[4]Committee on OR, national research council. OR with special reference to non-military applications. Physics today. 12-16, Sept. 1951.

studies the total economy of the United States in a quantitative manner using linear equilibrium analysis (input-output analysis).[5] By means of this method actual or hypothetical changes in one sector of the economy can be introduced and their effects on all the other sectors can be quantitatively determined within the limits of the necessary restrictions and simplifications inherent in the analysis.

Methods of Operations Research

The methods used in OR are, as mentioned earlier, principally those of the investigative sciences. OR is usually both an observational and an experimental undertaking. The principal methods used can be classified several ways. First, let us consider a classification according to the physical character of the problem and its data.

Probabilistic. In this class are problems that exhibit the characteristics of random behavior. A classic example of such behavior is that of assigning the probability of a certain throw with a pair of dice. Considering only one die, it can be seen that any number from one to six is equally likely. This is a random variable. That number equal to the sum of the numbers on two dice (the stochastic variable) is of greater interest in a game, since all of its possible values are not equally likely. To illustrate, there are 36 possible combinations of the two numbers from one roll of the pair of dice. The sum 2 has only one mode of occurrence (1,1);

[5] W. W. Leontief. The structure of the American economy 1919-1939. (1951).

therefore, its probability of occurrence is one out of 36, or $P_2 = {}^1/_{36}$. The sum 7 can be obtained from (6,1), (5,2), (4,3), (3,4), (2,5), or (1,6), and its probability of occurrence is therefore 6 out of 36, or $P_7 = {}^6/_{36}$. In the example shown, the variables and the <u>distribution function</u> describing their occurrence are discrete; that is, they exist only as certain values (e.g., 1,2,3,..,6). In many situations the variables are continuous over some range. Many kinds of physical situations exist which fit well-defined distribution functions. An example is found in the measured dimensions of bricks drawn at random from a kiln. As is well known, the bricks are not all exactly the same size, and the measuring instruments are not always read the same way. However, the values will tend to group around an <u>average</u> brick size, with only a few values showing great spread. The distribution obtained is known as a normal distribution. Other common types of distribution are known as binomial (that of the stochastic variable in the dice game), and Poisson. Still other types of problems do not fit any known distribution and are specified as non-parametric. Probabilistic methods use these various distribution characteristics to evaluate and predict from statistical data.

<u>Deterministic</u>. In this class are included methods of handling problems with all factors controlled or controllable (i.e., not subject to random behavior). In such problems, all variables can be completely defined in mathematical terms. A simple example is the use of the calculus to determine the

minimum value of a function of several variables, such as the weight of structural steel in a variable size roof bay. Often the greatest gain by use of deterministic methods is in effecting a clear statement of the actual problem. The use of symbolic logic is helpful in this work.

Methods can also be classified on an operational basis. Thus the availability of data, the background and training of OR workers, the time and facilities available for work, the estimate of probable results, and other factors enter into choice of operational methods. A general operational classification would be:

Analytic. In this type, emphasis is placed on the organization and analysis of data from past observations. Predictions and recommendations are made on the basis of such analyses.

Synthetic. In this procedure, an early step is that of synthesizing a model, either mathematical or physical, which is analogous to the operational problem. This model is then used as a study and prediction device. The method most clearly indicates the process of abstraction common to scientific investigation, where major factors are abstracted from physical or operational systems and recombined in simplified forms (models) in order to conveniently observe their actions.

Most OR problems call for the use of both analytic and synthetic methods. A common procedure consists of the following steps:

1. Analysis of the operation (interpretation of data);

2. Formulation of model;
3. Testing of model for conformance with operation;
4. Manipulation of model to study effects of variations;
5. Formulation of recommendations.

It has been said that a researcher does three things. He acquires knowledge, he creates new knowledge, and he communicates new knowledge. The third activity is an important part of OR activity. In most scientific pursuits, the knowledge created is communicated to other scientists. In OR work, however, the knowledge must be translated into semi-technical or non-technical language and transmitted effectively to those responsible for operational decisions. Even the most brilliant theoretical successes can only be realized through the understanding action of an informed and sympathetic executive. Just as important is the necessity for good communication among members of an OR group. Since these members represent different disciplines, and different degrees of familiarity with the techniques used, the maintenance of adequate communication is a vital matter.

Mathematical Techniques

There are many mathematical techniques that have achieved wide usefulness in OR study. Most of these were originally developed for use in other scientific fields, but a few can be attributed directly to this work. These can be conveniently classified according to the character of the data presented. A few of those in common use are:

Probabilistic Techniques

Statistical Analysis

Waiting Line Theory

Game Theory

Search Theory

Theory of Decisions

Monte Carlo Method

Deterministic Techniques

Calculus of Variations

Differential Equations

Linear Programming

The techniques mentioned are well documented in the literature of OR and mathematics, with examples of their applications to specific problems. Any intensive examination of the application and validity of these is impossible here, as the various techniques represent highly developed work in diverse fields of applied mathematics. The following discussions are, however, an attempt to briefly sketch the nature and application of the more common techniques.

Statistical Analysis is most valuable when the solution of an operational problem can be attained most easily by the reduction of data obtained from observation. Such an analysis might be the organization and study of data relating to the quietest area in a building for location of a recording studio.[6]

[6]Further applications of statistical analysis are suggested in following chapters. For a general reference on methods see P. G. Hoel. Introduction to mathematical statistics. (1947).

Waiting Line Theory has found wide application in study of urban traffic problems. Another application of interest, discussed by Morse, is that of a waiting line at a restaurant.[7] Assuming a steady rate of serving (S), and a steady rate of *random* arrivals (A), he shows that even if the serving rate is 150 per cent of the (random) arrival rate there will be, on the average, a waiting line of two persons. Other interesting applications could be made to traffic or production flow, and to scheduling of construction.[8]

Game Theory is a relatively new and difficult technique. Some parts of the theory are well defined, particularly that of competition between two individuals or firms. The essential purpose of the actions indicated by the solution of such games is that of minimizing the advantage of one's competitor.[9] The theory should find application in the problem of location of competitive enterprises, particularly after the mathematical solutions are more completely mastered.

Search Theory grew out of wartime studies in naval and air tactics, such as submarine search. Its principal purpose is that of prescribing the most effective deployment of limited resources toward attainment of a specified goal.[10] The problems

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[7]P. M. Morse. Operations research. Applied mechanics review. 89-93, March 1954.

[8]An additional example of the application of this theory is discussed in the appendix of this thesis.

[9]An excellent introduction to the theory is J. D. Williams. The compleat strategyst. (1954).

[10]Morse and Kimball, op. cit.

of location of storage areas, tool cribs, and similar service areas in large-scale manufacturing plants or the larger problem of location of service groups for an entire industrial area should be amenable to this type of analysis.

Decision Theory is another fairly recent addition to the body of mathematical techniques. It rests on two concepts: first, the probability of a particular outcome if a given course of action is pursued; and second, the value of such an outcome. With these determinants, various actions can be explored and a quantitative best expectation chosen. A very important use of this theory should be found in planning for future expansion of large industrial establishments, where future processes, etc., are not completely known. Another application of possible merit is the use of decision theory in the programming of design efforts.

Monte Carlo Method. This is, as the name suggests, a gaming method. Briefly, it consists of using the known or inferred distribution functions of the data of an operation to develop large amounts of fictional data having the same statistical character as the observed data, and then running these fictional data through a model or models to test various modifications.[11] The method is very useful in situations where necessary amounts of observational data are costly or difficult to obtain but good distribution estimates are available. Because of this, it should be especially adaptable to planning

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[11]Notes from MIT summer course on operations research. (1953), 106-14.

and layout problems in stores and shopping groups. An interesting use of the Monte Carlo Method has been made by a group at MIT studying the operation of a power generation system.[12] Using statistical data on river flows, they have developed fictional data sufficient to "run" many years of hypothetical flow data through models of the system. In this way, many years' equivalent of testing and observation can be done easily and economically, with good representation of actual conditions.

The Calculus of Variations, Differential Equations and similar techniques are well established as appropriate in solving engineering and scientific problems. They are the basic tools for use where all aspects of a problem are determinable, or can reasonably be assumed to act so. As such, they are of wide usefulness in structural engineering even though newer probabilistic techniques could now better accomplish some tasks.[13]

Linear Programming is a new and powerful technique, although the limitations on its use are quite stringent. It is a procedure for determining the maximum or minimum feasible outcome of a linear system which has specific limits on its

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[12] E. W. Boehne. Applications of operations research in the power field. Electrical engineering. 655-8, July 1954.

[13] An optimal problem in structural mechanics is discussed in Bertram Klein. Direct use of extremal principals in solving certain optimizing problems involving inequalities. Journal, Operations research society of America. 168-75, May 1955.

various components of input and output.[14] One of the applications of linear programming has been in the oil refining industry. The extraction of various salable products from crude petroleum is dictated by market prices, demand, extraction process limitations, and costs, and the relative amounts of different products extracted per barrel of crude petroleum are related in a complicated fashion. By use of linear programming methods it is possible to devise the combination resulting in maximum profit.[15]

The examples which have been given for the various techniques do not necessarily illustrate their best use, but only possible applications.

Simulators and Computational Processes

The operational processes used in applying these various techniques have undergone great changes in the recent past. Indeed, the acceptance of many techniques, especially Monte Carlo method and linear programming, has been due to their use of simulators and computing machines, to a large extent. These processes are discussed briefly below.

Data Generators and Simulators can be physical models (often mechanical, hydraulic, or electrical systems) having the same characteristics as the operation under study. One example of this sort is the network analyzer used to study

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[14] A. Charnes, W. W. Cooper, A. Henderson. An introduction to linear programming. (1953).

[15] In the appendix of this thesis a problem in plant organization and circulation is formulated.

electrical transmission systems. This analyzer reproduces, at small scale, the essential loads and sources of the system and allows easy modification to facilitate experiments. Mathematical models can also be used as data generators or simulators, in which case the various operations of addition, multiplication, integration, etc., correspond to the actions of the physical system. The use of the equations for deflection or stress of a beam, together with data on the variables (span, loading, etc.) is an example of use of such mathematical models. The use of geometrical (graphic) methods is another important one.

Computational Processes are a basic key to the growth and widespread application of mathematical techniques, and hence to OR. Matrix theory, which effects a shorthand treatment of complicated mathematical relationships, is directly useful in computation (e.g., the determinant solutions of simultaneous equation systems familiar in structural analysis are akin to matrix methods). In addition, matrix techniques serve to organize numerical data conveniently for use in computing machines. When systems become large and complicated, or when equations can only be solved by methods of numerical approximation, the use of computing machines becomes a necessity. There are now many sizes and varieties of these in use. They can be classed by type of operation as:

Mechanical

Electronic

or by the system of units or measure used, as:

Digital (using discrete numbers)

Analog (using continuous variation).

The desk calculator is a mechanical digital machine, while the famous UNIVAC is an electronic digital machine. The network analyzer mentioned above as a simulator is essentially an electronic analog computer, while a slide rule is a mechanical analog computer. There is nothing ominous or mysterious about computers. Some have recording (memory) systems to enable them to carry and use tabulated data (e.g., tables of trigonometric functions). All of them, however, depend solely on the skill of the person doing the programming. The *age of the electronic brain* is more correctly the era of highly developed human intelligence aided by labor-saving equipment.

Thoughts on the Use of Operations Research in Architectural Planning

Organizational Patterns

In the previous sections the application of OR techniques to various design and construction problems has been discussed. There remains only to consider the organizational arrangements involved. It is well to consider the position of the architect in the planning of a proposed industrial or commercial complex. Two alternatives seem all too typical. Either, 1) the architect is not commissioned until many of the basic planning decisions have been made by the client and his advisors; or, 2) the architect is called in as a sort of all-seeing savior at the beginning and has the task of developing a program (and at the same time finding out what the client really wants, as contrasted to what he talks about). It would seem that neither solution is wholly satisfactory. At this programming stage the OR method seems very useful. An OR group, including persons versed in the various phases of basic planning problems, can study the client's operation and recommend a program of action, thus relieving the architect of the staggering programming task, and of the need to observe and understand methods and processes in which he has no background. Most important, the architect, as a member of that OR group, can be in a position to guide basic program recommendations and thus alleviate the danger of program decisions which are in opposition to later design objectives. Such a team approach should lead to better planning. Indeed, it is sometimes practiced, when a far-seeing client and architect get together and retain consultants from other disciplines. The lack, at this time, seems to be a framework of organization and precedent, so that such teamwork could be the rule, rather than the exception.

Let us now consider some possible organizational patterns for developing an alliance of OR and architecture.

A Composite Firm. This could be essentially an OR group functioning as planning and design consultants and sharing the same roof with an architectural firm. The architect would serve in a double capacity, being a member of the consultant OR group and also the executive member of the design firm.[16] Operation might be as follows:

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[16]This pattern of organization is further developed for a particular problem in chap. 4.

1. A prospective client approaches the firm with plant expansion in mind.
2. The OR group initiates a survey to determine the nature of the operation involved.
3. The OR group, its personnel tailored to the nature of the problem, undertakes a study of the entire operation involved, with the aims of understanding and evaluating needs.
4. The OR group submits its recommendations (possibly through the architect as spokesman) to the client as a proposed general program.
5. The client makes his decision, possibly from among alternates submitted by the OR group, and with consideration of the intangible factors not considered by OR.
6. The architect, acting now as head of the design firm, proceeds with design on the basis of the accepted program.

Probably the OR group would continue to function, after step 6, as consultants, with suitable changes in personnel (e.g., the inclusion of structural and mechanical engineers, etc.). However, at this time they would effectively become a staff functioning under the architect as executive, whereas in the programming stage the group, including the architect, would be functioning as consultants to the client as executive. The concept of a design consultant staff is of course well known and applied in current practice. The introduction of some of the spirit and technique of OR work might be of advantage, however.

There are several objections apparent to this type of organization. First is the legal and ethical question -- Does the presence of the architect in the group concerned with policy recommendations to the client leave the architect open to attack on charges of biasing recommendations in his favor? There is also the objection of the client to opening too much of his business to the scrutiny of outsiders. Finally, there is the possible objection of the architect to losing a part of his freedom of action. Let us now consider a second pattern which avoids some of these objections.

Cooperation between an Architect and an Internal OR Group in the Client's Firm. In this pattern, the sequence of the earlier pattern could hold, with the exception that the architect would not likely be the spokesman for the OR group. Initial studies would be more easily done, due to the prior knowledge of the OR group. It is probable, though, that later stages of programming and design would be more difficult since the OR group would have greater mobility and fewer effective deterrents to continued modification of recommendations after a necessary design freeze date. Only a large enterprise is likely to have such a permanent OR group, which fact in itself limits this pattern to a small sector of practice. Finally, the very fact that an OR group is maintained within a company makes it likely that the company also has an architectural or plant engineering staff which is involved in the preliminary planning of facilities, thus diminishing or eliminating the influence of the outside architect as a temporary member of the internal OR group.

Thus it would appear that this second organizational pattern is not generally feasible. Let us proceed to examine a third possibility.

A Separate OR Group with an Architect Member. This pattern suggests that OR consultants such as the present firms, with the addition of an architect to the group, would undertake the steps 1, 2, 3, and 4 of the earlier sequence. After acceptance of the program of recommendations by the client, an architectural firm would be commissioned for the design job. If the architect involved in the OR group was also represented in the design firm, the same possibility of bias would exist as in the first pattern. Even if the architectural firm in control of design was not represented earlier on the OR team, two gains could result, namely, the use of OR techniques in solving the client's problem, and the availability to the OR group of the experience and knowledge of the architect-member. However, the resulting separation of programming and design could result in piecemeal and sterile design and in poor cooperation.

It would seem that this organizational pattern would work effectively in a situation (as an example, an oil firm) where the consulting firm or the company itself was involved in OR studies and in process planning, and the architectural firm was commissioned only to design the building shell. Such a situation sometimes exists (often in government work) but is of no particular credit to the architectural profession. Something less than full professional ability is sufficient for such tasks.

On consideration, it would appear that the first pattern of organization was the best from an overall standpoint of coordinated planning.

Personnel Requirements

The enlargement of organization is a factor to be considered. Restricting ourselves to consideration of a practice in industrial architecture for the moment, we can estimate the size of such a group. The disciplines, knowledge, and experience required would for most purposes include OR techniques and methods, mathematics, statistics and computing; engineering and science as applied to industrial problems; economics; finance and business management; sociology and psychology; regional and urban planning; architectural design; and construction. It is possible that a group of four to six persons with proper background could cover this range. A hypothetical combination might be a mathematician with experience in OR, a chemical engineer, an economist experienced in industrial planning, a sociologist with experience in labor relations, and an architect. Such a group would need several junior members engaged in data collection and processing. The group would not necessarily be full-time associates but should work together often enough to develop group responsibility.

Supplementary Areas of Application

Several other areas exist for application of OR to architectural work once such an alliance is created. One such opportunity is an OR study of the design organization and the scheduling of design effort. By these means a firm could literally lift itself by its bootstraps through rational self-examination. Another type of work lies in the field of research on construction materials and methods. OR techniques might provide a way of speeding research which heretofore has lagged.

Conclusions

Architectural Education

Proceeding from the assumption that an alliance between the fields of OR and architecture is desirable, we can consider the changes in architectural education which might be helpful in developing this alliance. As was mentioned earlier, most writers on OR work stress the need for scientific orientation. This does not mean, however, that all members of an OR group should necessarily be adept in the application of the various techniques in addition to competence in their own fields. The purpose of the OR group is, after all, to eliminate the necessity for such super-humans. What is implied is that all members of the group must be sympathetic with *scientific method* and the reservation of judgment which it implies. It is at this point that the case for inclusion of the architect in the OR team may break down. To quote (and paraphrase) a statement from Morse, "The scientist must always be sceptical and is often impatient at arbitrary decisions; the administrator [architect] must eventually make decisions which are in part arbitrary and is often impatient at scepticism."[17] To this writer it seems that the task of education lies in developing, in the architects, an awareness of the implications and value of scientific method (at least insofar as can be applied to architecture of complex function). Without presuming to discuss the other capabilities of the architect in the practice of his discipline, one might generalize that his worth as a member of an OR team depends on his recognition of the complexity of practical problems and the value of contributions from other fields towards their solution.

Qualifications of Other Personnel

Parallel to the necessity for increased awareness of scientific methods on the part of the architect, there exists a responsibility for concern with the problems of building, on the part of the other members of an OR group. In the case of scientists, this implies the sort of person interested in practical problems and adjusted to the pace and close scheduling of design and construction.

Areas of Practice

It is not likely that an alliance of OR and architecture would be of much value in the part of architectural practice concerned with small buildings, or with buildings in

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[17]Morse and Kimball, op. cit.

which the functional requirements are simply satisfied. The real worth of such an alliance should occur in large commercial and industrial projects, and perhaps in institutional facilities. Another important area susceptible to this combined effort would be urban planning and housing, if the necessary administrative system was functioning to insure action on proposals.

<u>The Challenge of the Future</u>

The proposals sketched in the foregoing pages are intended as a thought-provoking suggestion of direction, rather than as a specific proposal. The buildings of tomorrow are likely to be more complex than those of today, and the economic pressures are likely to be more extreme. The place of the architect in designing these complexes will be determined by his ability to master their problems. A more direct relationship with scientific endeavor seems (to this writer) necessary in order to develop this capacity.

Another interesting possibility is apparent. The efforts made by architects to appreciate the problems of other disciplines will probably result in increased interest in architecture on the part of others. This should aid all aspects of the practice of architecture.

CHAPTER IV

DESIGN PROGRAMMING -- THE FRAMEWORK

Design Organization and Responsibilities

Phases of the Design Process

The process of design which precedes and makes possible the realization of a building project is commonly separated into parts, or phases. In the smaller projects familiar to architectural practice the logical division is that of preliminary and final design. Preliminary design, in this sense, signifies the delineation of all major elements and aspects of the proposed building project; the details and minor aspects are deferred for later consideration (after the designer has assured himself of their feasibility). With large and complex projects, however, this division is not particularly applicable.

To a large extent, for the smaller projects, preliminary design involves the conception of entire alternative solutions for evaluation. For complex projects the early work includes many planning decisions not architectural, while the actual design is a more nearly continuous process leading toward the fully conceived solution. For this reason it is convenient to use other terms for the divisions of effort on large or complex projects. One common usage is that of _scope_ and _design_. Another, which will be used here, is _planning_ and design, signifying the gross and detailed portions of the development of a solution. This designation is appropriate since the gross aspects of the problem for consideration include several factors commonly known as planning: regional planning, site planning, and economic planning.

In the work to follow, planning will refer to consideration of the broad aspects of a problem, generally relatively free from constraints, with the intention of defining a region for concentrated study. Design will refer to detailed consideration of items, systems, and schemes within the regions defined by the prior planning efforts.

Organization of the Planning Phase

Scope of Work. The planning phase of the design of a power station could be a major or a minor part of the work of a design organization, depending on the role played by the client. For this project, the assumption is made that the client, an independent electric utility firm, has decided to commission the entire work, including feasibility studies. Planning work then must start with the analysis of present and probable future demand for electric power and the capability and condition of present installations. Upon this information as basis must be built an analysis of desirable new capacity, together with study of location, type of systems, type of loading, and accessory considerations. The planning group must study the organization of various required facilities for the station, and the requirements of transportation, personnel, and health and safety. Financing and construction arrangements must be considered. The client firm will be responsible for furnishing data on operations and needs, as requested by the group. The planning group must conclude its studies with the presentation of a complete set of design criteria for the proposed station, covering all major decision problems. This set of recommendations, when approved by the client, will become the charter for the succeeding design group.

Client-Planning Group Relationship. The relationship between client and planning group is necessarily of a consultant type. Since the client is contracting for professional advice, and is opening his business to the scrutiny of others, the consultant's advice, and the enabling study, can be likened to the feasibility studies for a bridge or highway, or the marketing studies for a new product. Only in this manner can the professional planner and designer participate in the early stages of such a project, before any decision has been reached on the advisability and scope of building plans.

Organization and Personnel. The organization of a research and planning group for the initial phase of this program should follow in general the first pattern discussed in Chapter III -- that of an Operations Research team which is part of a composite firm. Most of the work included in the scope of the planning phase is well suited to quantitative analysis and to collaborative study. It is important for the continuity of any ensuing design project that several members of the consultant planning group be permanent members of the design firm. These should include the architect and at least one of the system design engineers. One of these men should act as group leader of the research and planning group. For convenience of organization, the group should be a temporary department of the design firm. Specialists from other fields, not regular members of the design firm, would be included as temporary associates. The group should contain five to eight members, depending on the individuals' backgrounds, and should embrace the following disciplines: architectural design and construction, engineering (nuclear, power -- electrical and mechanical), economics and regional planning, OR methods, real estate and finance. Additional consultants to the planning group may be needed for professional advice on matters such as transportation, health and safety considerations, or insurance.

Figure 2, Planning Phase Organizational Chart, shows the proposed organization. Two lines of communication are indicated between client and consultants. The line connecting with the client's liaison representative would be the working contact for data transfer and conference.

Organization of Design Phase

Scope of Work. The work of the design phase consists in translating the scope information presented in the recommendations of the planning group into a complete detail design for the entire facility. The scope information will include site location, generating capacity, loading and control arrangements, general choice of systems types, extent and nature of accessory and auxiliary facilities, and general design

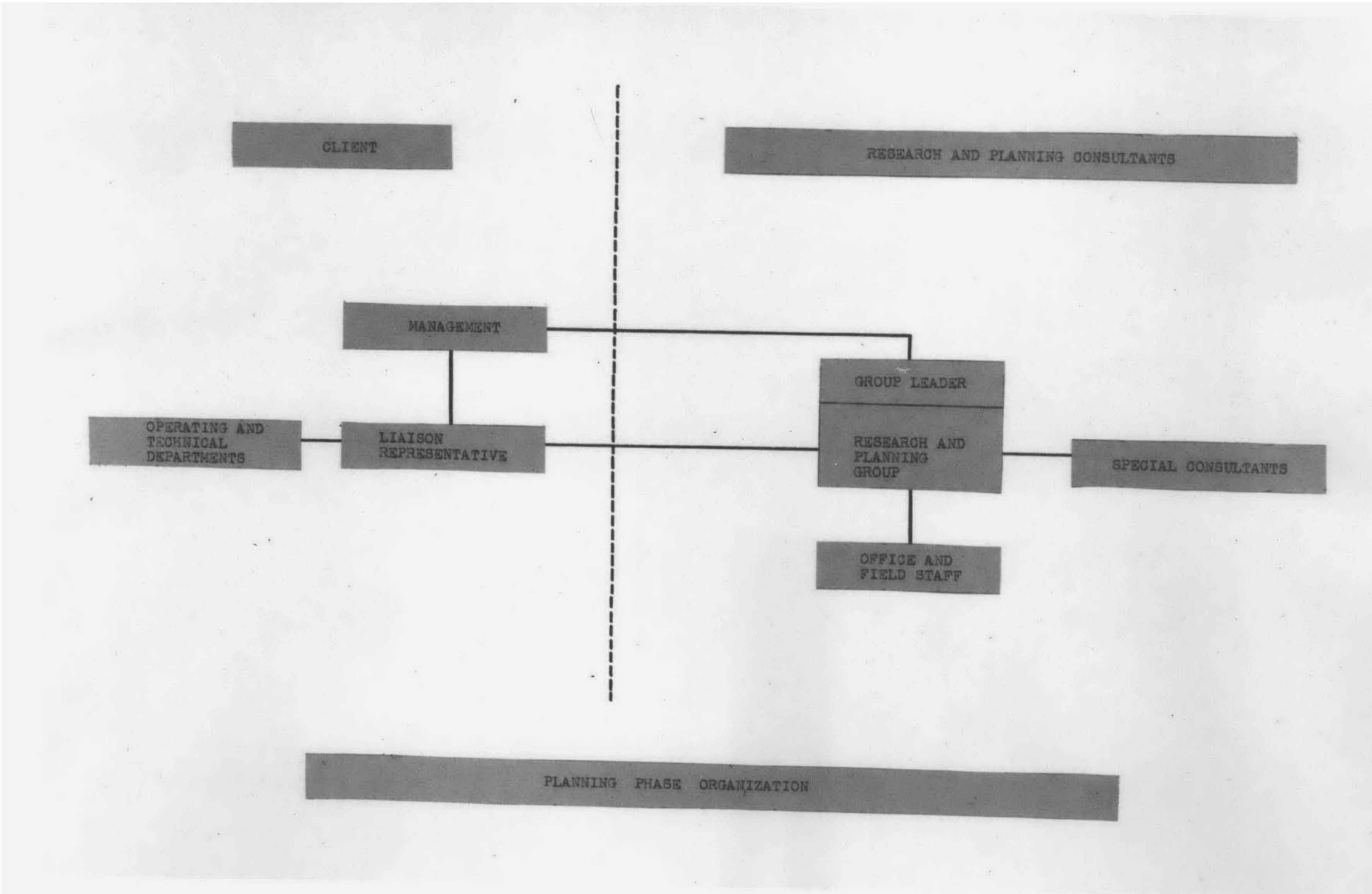
CLIENT
RESEARCH AND PLANNING CONSULTANTS
MANAGEMENT
GROUP LEADER
OPERATING AND TECHNICAL DEPARTMENTS
LIAISON REPRESENTATIVE
RESEARCH AND PLANNING GROUP
SPECIAL CONSULTANTS
OFFICE AND FIELD STAFF
PLANNING PHASE ORGANIZATION

Figure 2

requirements such as safety standards.

Client-Design Group Relationship. The relationship between client and design firm is that of a conventional design services contract. Due to the large scale of the design effort and the lack of precedent for parts of the systems, the contract should be of a cost-plus-percentage or cost-plus-fixed-fee type. Such an arrangement will also simplify arrangements for outside consultant services.

Organization and Personnel. The organization of the design group for this project should generally follow the lines of conventional office practice. Some complications are introduced because of the dual nature of the design job -- on the one hand the design of an industrial type plant facility with buildings, outside structures, and extensive site work, and on the other hand, the design of a production system, or systems, for a single purpose. As is commonly the case with industrial facilities, the design and construction (including purchase and fabrication) cost of the production systems is much greater than that of the buildings and other facilities. At first thought it might seem that the responsibility and initiative of design coordination belong to those involved in design of the production systems. However, these individuals or groups are each only involved in a particular part of the entire job, destined to connect to other parts of the system. Only the architect, responsible for providing space, enclosure, and structure for the entire facility, is in a position to coordinate the work of all groups. Being equally responsible to all of the systems design groups, the architect is in a position to resolve interferences and conflicts such as space use and location. Members of the architect's design staff should function as coordinators in their relations with the other design staffs.

Figure 3, Design Phase Organizational Chart, shows the proposed organization. It should be noted that the heads of the various design groups are shown to act together as a design team. Matters of design and other technical difficulties are to be decided at this level. An OR consultant with his staff are attached to the team, as many of the design decisions must be based on quantitative analysis. The project manager will be responsible for the entire design phase of the project, except that most matters of design will be settled by the team. The project manager will also be responsible for the part the design firm plays during the construction phase of the project.

Systems Design

Much of the detailed design of the reactor, fuel processing, and steam generation system will likely be contracted out to firms specializing in engineering and fabrication of these components. (Many of the large manufacturers of boilers and turbines are entering this field.) These companies will have the necessary development and testing facilities, as well as the technical background. Control and coordination of these efforts will be an additional responsibility of the design group.

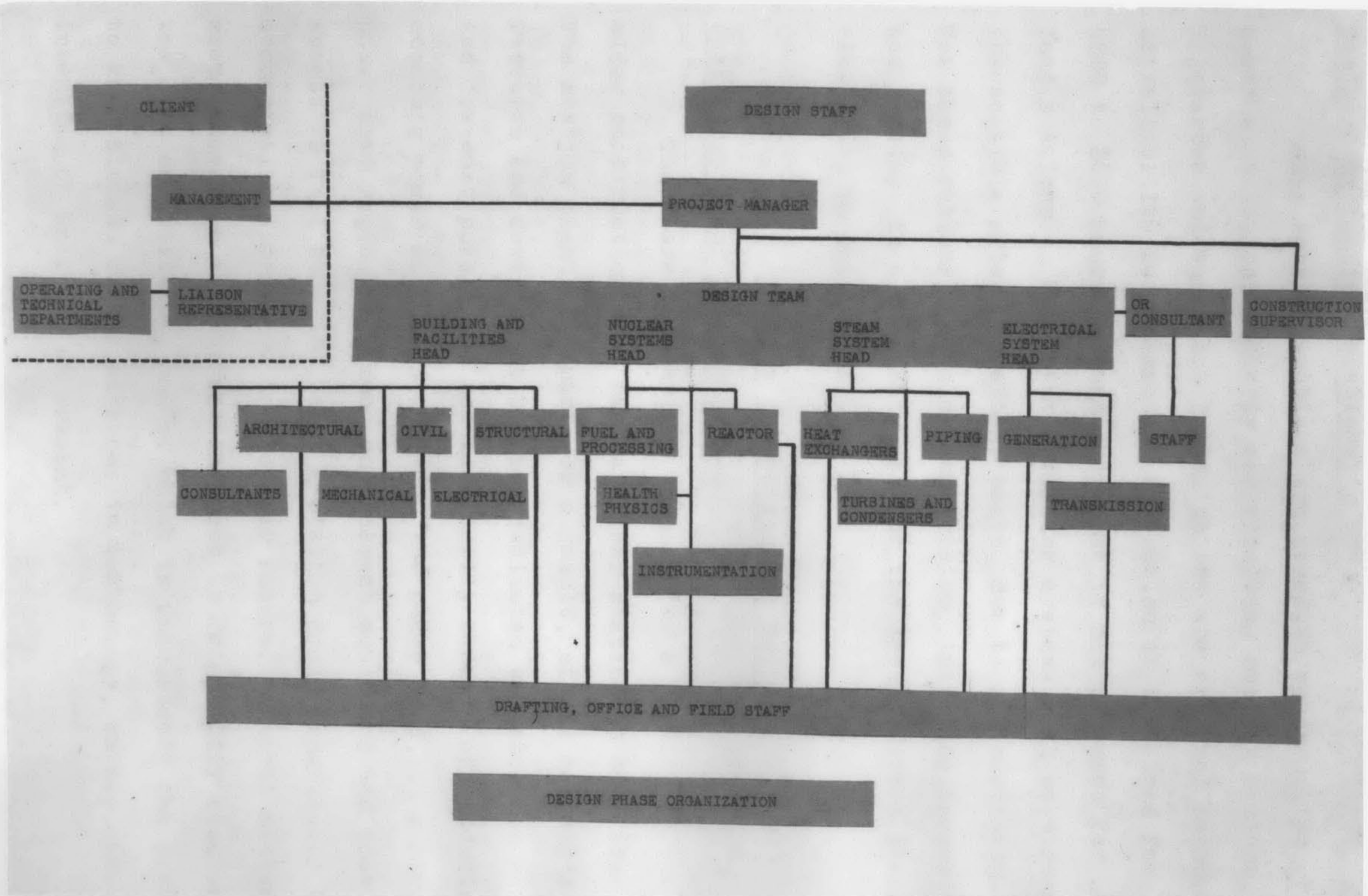
CLIENT
DESIGN STAFF
MANAGEMENT
PROJECT MANAGER
OPERATING AND TECHNICAL DEPARTMENTS
LIAISON REPRESENTATIVE
DESIGN TEAM
BUILDING AND FACILITIES HEAD
NUCLEAR SYSTEMS HEAD
STEAM SYSTEM HEAD
ELECTRICAL SYSTEM HEAD
OR CONSULTANT
CONSTRUCTION SUPERVISOR
ARCHITECTURAL
CIVIL
STRUCTURAL
FUEL AND PROCESSING
REACTOR
HEAT EXCHANGERS
PIPING
GENERATION
STAFF
CONSULTANTS
MECHANICAL
ELECTRICAL
HEALTH PHYSICS
TURBINES AND CONDENSERS
TRANSMISSION
INSTRUMENTATION
DRAFTING, OFFICE AND FIELD STAFF
DESIGN PHASE ORGANIZATION

Figure 2

Design-Construction Relationship

Many special problems are posed in construction of a power station, particularly one involving nuclear systems. Tolerances and equipment installations are critical because of reliability requirements. (Operation at full load for 4000 to 8000 hours between shutdowns is not uncommon for base load stations.) Many of the reactor systems will be virtually inaccessible after operations begin, due to radioactivity. For these reasons, detailed supervision, including inspection and testing, is a necessary part of the design firm's responsibilities to the client.

Factors in Decision to Build

Justification of Nuclear System

There are two obvious reasons for a utility to consider construction of a nuclear power station at this time. The station might be a part, or a result, of the company's research and development program dedicated to better service and low-cost power, and not necessarily capable of producing economic power at the outset. On the other hand, in a high power cost region with much obsolescent equipment and poor access to fuel supplies, such a station could conceivably be economically attractive in the near future. Several motives seem evident in the current interest in feasibility studies on the part of utilities, one of which is undoubtedly the desire to keep abreast of the advances in technology, rather than any intention of building at present.

As evident from Chapter II, nuclear power stations are certain to be more complex, more difficult to control and maintain, and of costlier construction than present conventional stations. Fuel cost savings, then, are the short-range incentives and fuel resources the long-range incentive for nuclear stations. A second foreseeable incentive for construction of nuclear power stations is a by-product market for excess fuel from breeder reactors and for fission products. The development of nuclear ship propulsion systems seems certain and nuclear propulsions for trains and aircraft may be feasible; both would be ready markets for excess fuel from breeder reactors. Irradiation processes for sterilization and for treatment of materials may provide a market for gross or separated fission products and thus ease the problem of disposal of reactor wastes.

The evaluation of these factors is principally an economic problem, but one which can be attacked by group effort in the early planning of a project. The final decision is that of the client, based on the group recommendations.

Analysis of Demand

The analysis of demand is principally a problem in marketing research and is thus an appropriate study for an OR group and in particular the province of the regional planning member. The study would have three objectives: the analysis of present demand (quantity and location) and the efficiency of present supply; the analysis of future demand (quantity and location) due to growth and change; and the analysis of replacement capacity required to retire obsolescent equipment, as a function of the power cost of the new capacity.

Establishment of Program

A determination of new capacity can be made on the basis of the completed demand analysis and estimates of the power cost of the proposed nuclear station. Study of the probable economic size of plausible station designs would lead to recommendation of the size and number of station units.

The choice of site for a proposed station (or stations) is a location analysis problem with four important parameters: transmission cost (location relative to probable load center), transportation cost, cooling water cost, and cost of hazard reduction measures (isolation). As a theoretical study it is a problem in optimization of a function with these parameters. As a practical analysis, however, a restricted approach is probably necessary since significant patterns of land and water costs would be difficult to derive.

One restricted approach to the analysis that might be followed is described briefly. Starting from educated guesses of location relative to probable load, several sites are selected for their suitability as regards isolation of hazards and availability of cooling water. The cost of isolation (site purchase costs), of cooling water, and of transportation of supplies can then be computed for each of these locations as contributions to the production costs of the new station. Combining these with estimates of the production costs which are invariant with respect to location provides values for total production cost at each of the feasible sites.

The first of these feasible locations is then added to a model of the existing utility system and the system is analyzed according to a chosen demand pattern (determined earlier). The optimum (least cost) allocation of production among the various stations of the system is determined as a function of production and transmission costs and the total cost of this allocation is noted for various levels of demand. (A method of determining such least cost allocations is described by Westfield.)[1]

The other feasible locations are likewise introduced into the system one at a time and their optimum allocation costs are noted. Upon comparison of these analyses, the location resulting in lowest total system cost for significant demand levels can be selected.

Such a formulation would be, as mentioned earlier, restricted and would not necessarily lead to a fully optimum site selection, but only the best of the previously selected choices under the restrictions of the method. Further, it would only apply to the special case of a nuclear station with its comparatively minor transportation requirements.

Complete formulation and solution of the location analysis problem would be the task of the planning group as a part of their studies.

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[1]Fred M. Westfield. Marginal analysis, multi-plant firms, and business practice: an example. The quarterly journal of economics. 253-68, May 1955.

CHAPTER V

ILLUSTRATIVE STUDIES -- PLANNING

Limitations of Studies

Scope

The studies undertaken in this chapter are meant to be illustrative in character, and to touch only on major problems and those unique to nuclear installations or power stations. Other decisions leading to the illustrative design solution are covered either explicitly in the explanation of Chapter VII or implicitly in the drawings of that chapter.

Validity

In these studies, the limitations noted in Chapter I are restrictive. Therefore, attention has been directed toward methods rather than conclusions. Data and formulations have been simplified for economy of presentation, and studies necessitating active participation of collaborating specialists have been treated in elementary form.

Site Selection

The generalized problem of site selection, including discussion of load orientation (transmission) and transportation problems, has been discussed in Chapter IV. In this chapter only factors entering on the site selection for an illustrative design solution will be explored.

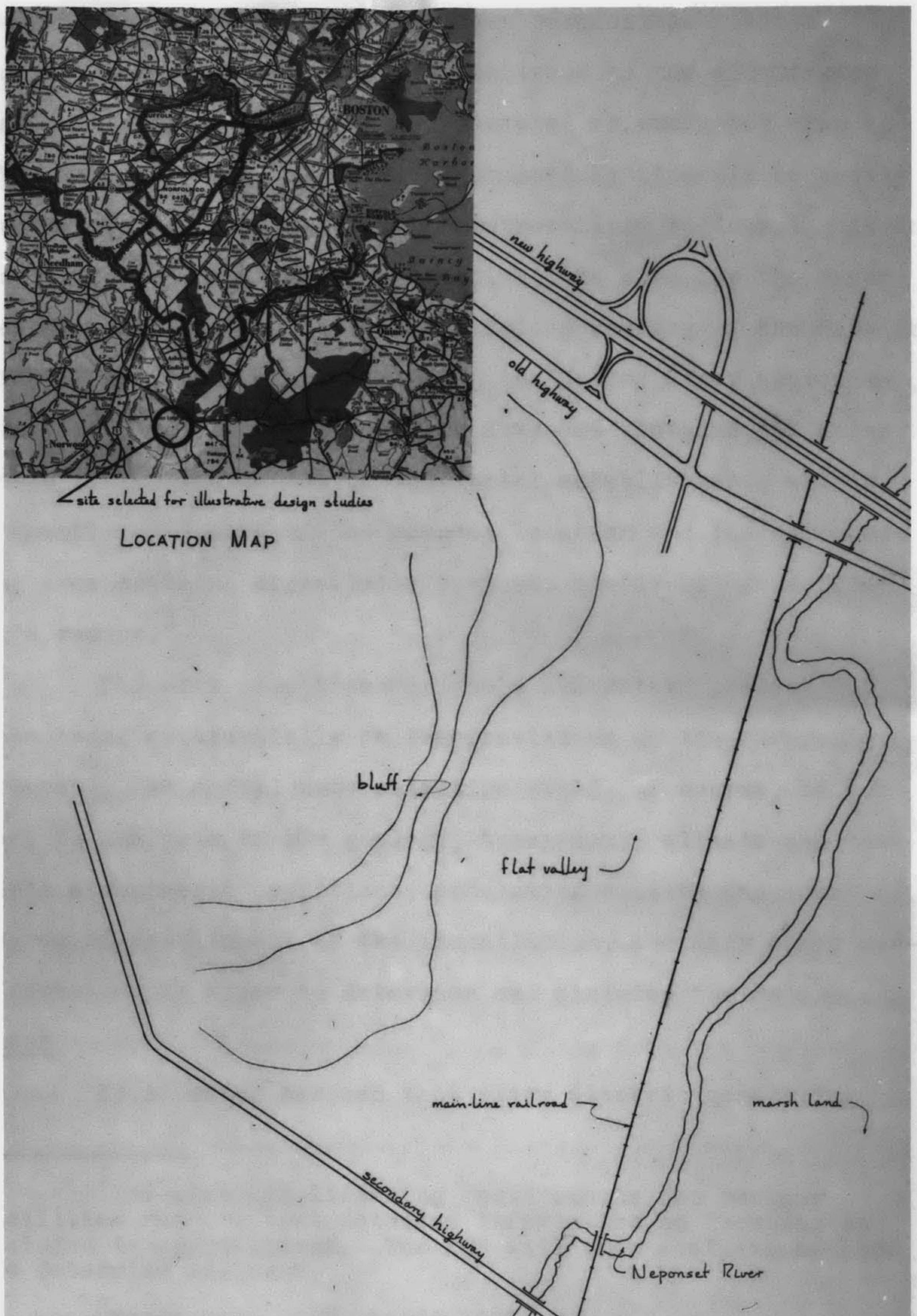
Description of Selected Site

The selection of a site for this illustrative design has been arbitrary. The various requirements that were imposed on selection are discussed below. No attempt was made to determine an optimum or near optimum combination of these factors. This shortcoming does not seriously affect any detail considerations of the site, but only the overall economic value of the project.

The site chosen for this hypothetical design lies approximately 12 miles south of downtown Boston on circumferential highway #128. (See Figure 4 for map and layout.) It is bordered by highway #128 on the East, Canton Street on the West, and is traversed by a main-line railroad. Only the central strip of the site adjoining the railroad is level. This portion is being presently developed as an industrial center. However, without serious difficulty or dislocation the site could be expanded east and west to embrace several hundred acres for isolation purposes, as there are no dense residential sections in the immediate vicinity. All improvements of this site area will be ignored for the purposes of the illustrative project. At the western edge of the industrial development the site rises as a sharp bluff and rolling wooded terrain. The Neponset River flows through the site.

Hazards

The potential danger from reactor installations has been discussed in Chapter II. No precise formulas or



PLAN OF SITE SELECTED FOR ILLUSTRATIVE DESIGN PROJECT regulations are available to govern permissible reactor locations.[1] (An old formula established by the AEC Reactor Safeguards Committee is not applicable; an exclusion area of the order of 50,000 acres as determined by it would be costly and practically unattainable in metropolitan regions.)[2] As an indication of possible good practice, the site for the power reactor proposed by Consolidated Edison Company of New York is cited. The site selected lies on the Hudson River approximately 25 miles north of New York City and contains 350 acres. There are no residences or industrial establishments within a quarter of a mile of the reactor location and the surrounding area contains approximately 45,000 people within a five-mile radius.[3]

The site selection for the illustrative project has been based substantially on the provisions of the foregoing proposal. An actual site selection would, of course, be subject to analysis of the geology, topography, climate and possible atmospheric conditions, population density and location, degree of containment of the installation, and many other considerations in order to determine and minimize the hazards.

Water

It is often assumed that steam-electric generating

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[1]The proposed licensing requirements for nuclear facilities require that detailed information on location be included in applications. The AEC will then evaluate hazards and determine adequacy.

[2]Nucleonics. 78, April 1954.

[3]Nucleonics. April 1955.

stations are not water-oriented since they are built where hydro-electric plants are not feasible. In actuality, due to the need for an efficient condensing system for the steam cycle, ample water is an important determinant of steam-electric station locations.

For the special case of the nuclear station the hazard criterion appears to overweigh the water supply requirements in determining location. Adequate natural water resources for once-through cooling are only found at oceanside locations, or on large rivers, both of which are heavily populated near urban regions. Artificial lakes have been constructed for power plants. However, based on estimates by Gaffert, it appears that a pond of the order of 500 acres would be minimum for a station of 180,000 kw capacity.[4] For the present arbitrary site selection, the use of recirculating cooling water with cooling towers or spray ponds is proposed. The river running through the selected site is assumed to maintain a sufficient available supply for make-up of cooling water losses and for all process water. For a 180,000 kw station this requirement is estimated as 5,000,000 gallons per day. A rough estimate of the Neponset River flow shows this requirement to be 5-10 per cent of total flow.

An alternate proposal for cooling water supply is that of bringing ocean water to the site. An 18 inch pipe line extending 12 miles to the sea and including pumping stations

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[4] G. A. Gaffert. Steam power stations. (4th ed. 1952), 140.

might cost on the order of $500,000, or $3 per kw of station capacity.

Load Orientation

The general problem of electric load was discussed in Chapter IV. The site chosen for this illustrative design is situated near existing high voltage transmission networks serving the metropolitan area into which the hypothetical station could be connected. Inasmuch as existing central stations serving the region are located near the seacoast while considerable residential and industrial growth is occurring inland, the inland site, although determined arbitrarily, would appear to be reasonably located with respect to load.

Transportation

Two problems demand consideration: 1) transportation for fuel, supplies, and wastes for disposal, and 2) access for employees, officials, and visitors. For the site selected a short spur line will provide railroad access. (A siding is being provided for the industrial center development of the site.) Motor truck transportation, as well as access by private automobiles and public transportation, is convenient through use of route #128, a four-lane highway.

Selection of Systems

Production Capacity and Availability

Chapter IV included a discussion of the general problem of capacity determination as an economic problem, as well as a discussion of the justification for a nuclear-reactor plant. In this illustrative project a rated capacity of 180,000 kw will be assumed as an established requirement. An availability of 80 to 85 per cent will also be assumed in accordance with typical experience for conventional steam-electric stations.

Reactor System Selection

Many reactor systems have been devised and studied with regard to their application in power stations. In selecting a system for this illustrative design, the five types chosen for the present AEC five-year development program have been considered[5] as well as another, the liquid metal fuel reactor (LMFR) being developed by Brookhaven National Laboratories.[6]

The first of these five reactor types, the pressurized water reactor, is the type being built as a full-scale power plant. Because of the limitations of water as a coolant, the efficiency of this type is low and it probably has a limited future.

The second type, a boiling water reactor, also is limited to low thermal efficiencies by the use of water as a coolant. This type, which requires location of the entire turbine-generator within the shielded area, resembles a huge machine more than a conventional steam plant, and would require extensive mechanical engineering design work.

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[5] 17th semiannual report. AEC. (1954), 21.

[6] C. Williams and F. T. Miles. Liquid metal fuel reactor systems for power. Nucleonics. 11-3, July 1954. Also O. E. Dwyer. Heat exchange in LMF power reactor systems. Nucleonics. 30-9, July 1954.

The sodium graphite reactor (SGR), the fast breeder reactor, and the homogeneous reactor of the AEC program are more advanced types technologically than the other two, as is the LMFR. Of these, there is available more published information relative to the SGR and the LMFR that is suitable for the purposes of this study; therefore these will be studied further.

The SGR is a thermal reactor using enriched solid fuel elements, a graphite moderator, and a liquid sodium metal primary coolant.[7] The LMFR, also a thermal reactor, uses a mobile fuel of uranium 233 in molten bismuth, a graphite moderator, and a liquid bismuth metal primary coolant which also carries fertile material for the breeding of additional fuel.[8] The use of liquid metal coolants in these reactors permits high temperature operation which in turn allows (moderately) high steam temperature and pressure with resulting steam cycle efficiency improvement.

Upon comparing the two reactor types several disadvantages of the SGR are apparent. The first lies in the use of solid fuel elements which would require that the reactor be shut down periodically in order to change fuel elements.[9] Since a nuclear station would probably operate on a base load

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[7]C. Starr. Goal: economic power in 10 years. Nucleonics. 49, July 1954.

[8]Williams and Miles, op. cit.

[9]J. A. Bolton and P. T. Calabretta. How to load solid fuel reactors. Nucleonics. June 1955.

basis, a periodic shut-down is an undesirable restriction. One way of partially overcoming this objection is in providing two reactors, each powering part of the station's turbine-generators.[10] By this means, the effect of a periodic shut-down on the system capacity is lessened. This arrangement will be discussed further in Chapter VI.

The second disadvantage of the SGR as compared to the LMFR is a result of the first mentioned above. While the fuel elements remain in the reactor, their content of fission products is increasing with resultant magnification of the hazard accompanying a conceivable reactor mishap. Although containment serves as a means of controlling the spread of released fission products, only by decreasing the fission product inventory in the reactor can the absolute hazard be reduced.

The LMFR overcomes both of the disadvantages of the sodium graphite type by means of a circulating fuel system. The liquid metal fuel is continuously circulated between the reactor and a processing loop which serves to remove the fission products. In a like manner, the coolant-breeder liquid is also processed to remove the fissionable fuel created.

The coolant system of the two reactor types is similar in that both utilize a secondary coolant loop to isolate the radioactive primary coolant from the steam generators.

Figure 5 shows a flow diagram of a sodium graphite

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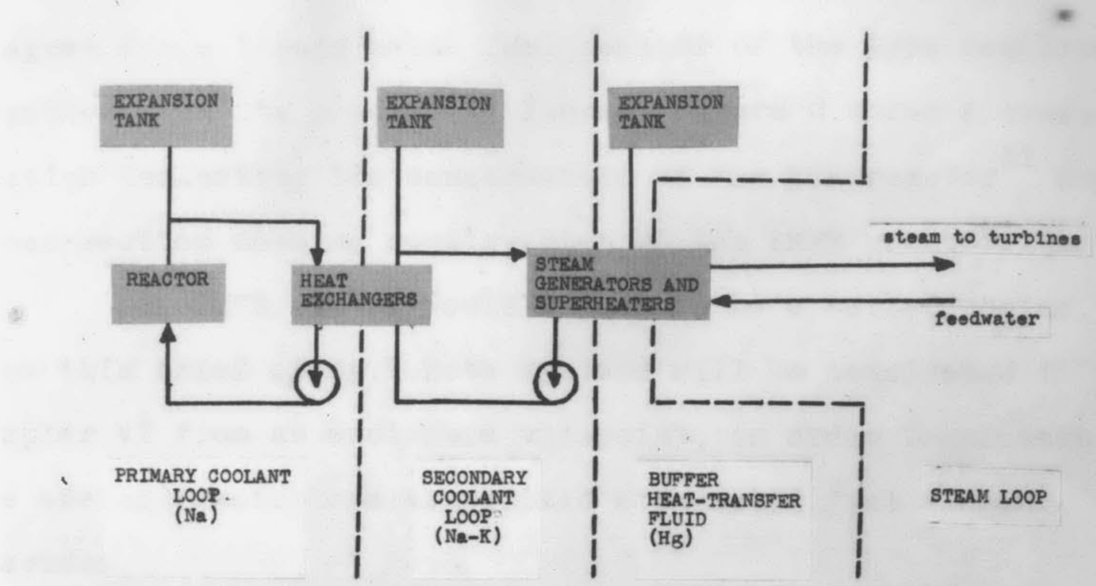
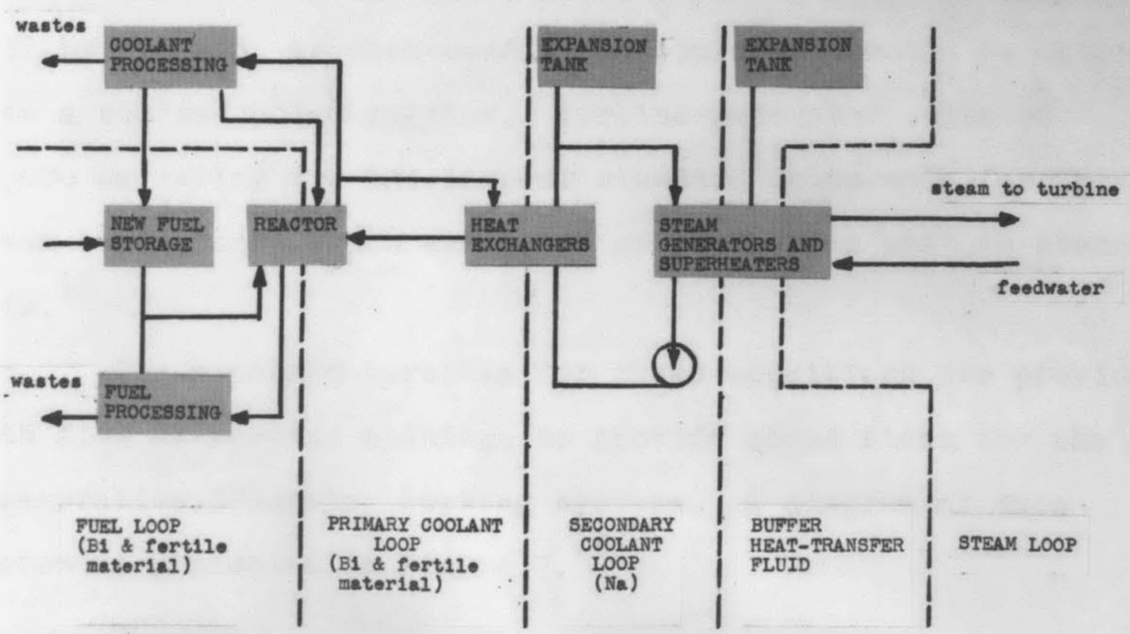
[10] A. W. Kramer (ed.). Highlights of atomic power developments in 1954. Power engineering. 58-61, Jan. 1955.



FLOW DIAGRAM-LIQUID-METAL COOLANT SYSTEM FOR SODIUM GRAPHITE REACTOR



FLOW DIAGRAM-LIQUID-METAL PROCESSING AND COOLANT SYSTEMS FOR LIQUID METAL FUEL REACTOR

reactor system such as described and the corresponding flow diagram for a liquid metal fuel reactor of the type described, together with its processing loops. Figure 6 shows a cross-section indicating the construction of the SGR reactor[11] and a cross-section showing construction of the LMFR reactor.[12]

The LMFR system would appear to be a better choice from this brief study. Both systems will be considered in Chapter VI from an enclosure viewpoint, in order to present the enclosure problems associated with solid fuel element reactors.

Determination of Other Systems

The choice of a reactor system effectively establishes steam pressure and temperature conditions for the turbines. Steam conditions of 850 psia, 900 degrees F. at the turbine will be assumed, as such conditions could apparently be obtained from a sodium-cooled reactor. Turbine-generator units of 60,000 kw rating are the largest standard units made for these steam conditions, which are below present steam station standards.[13]

The standard turbines for these conditions are provided with five extraction openings to provide bleed steam for the regenerative feedwater heating systems. A diagram of this system is presented in Figure 7.[14]

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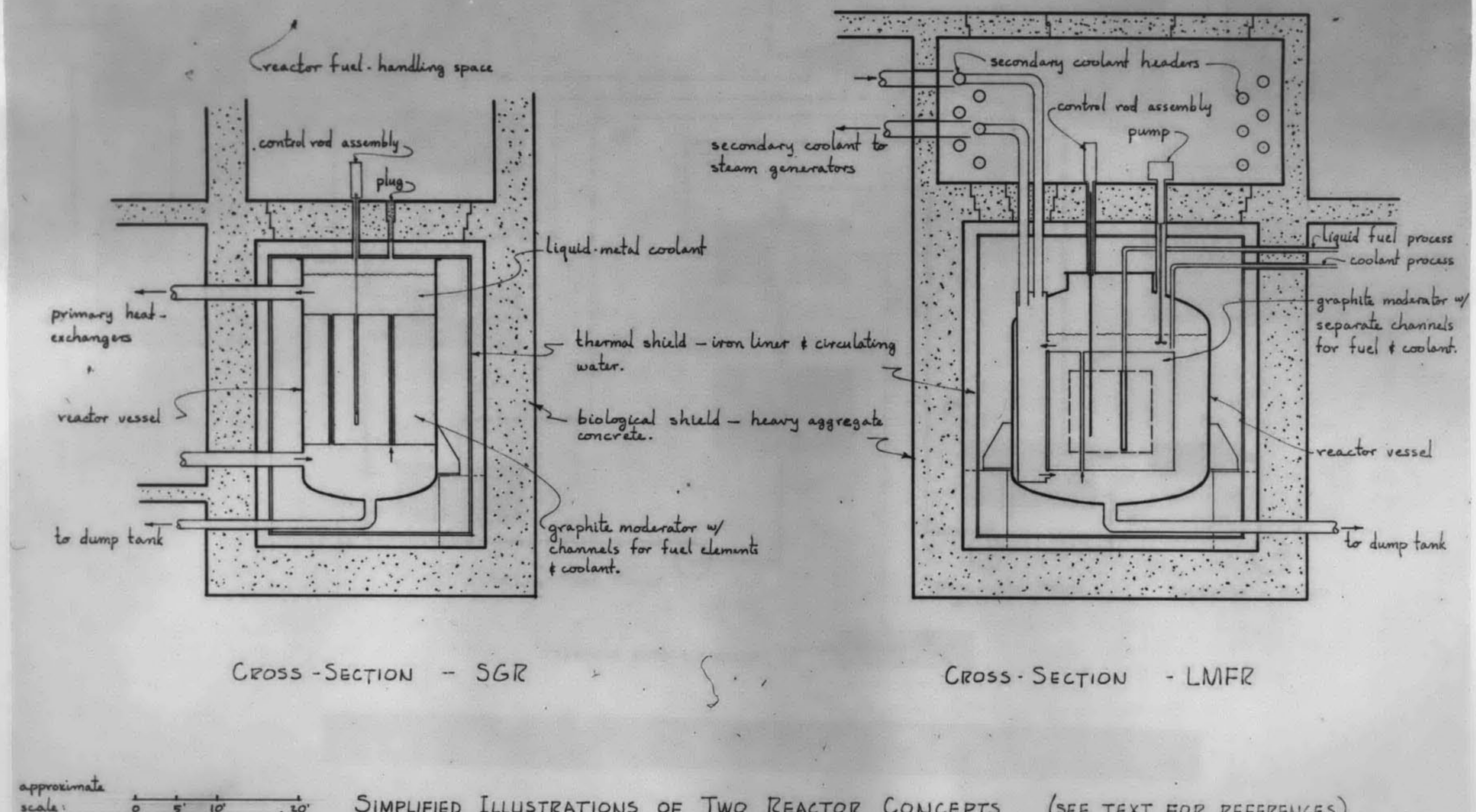
[11]Adapted from ibid.

[12]Adapted from Williams and Miles, op. cit.

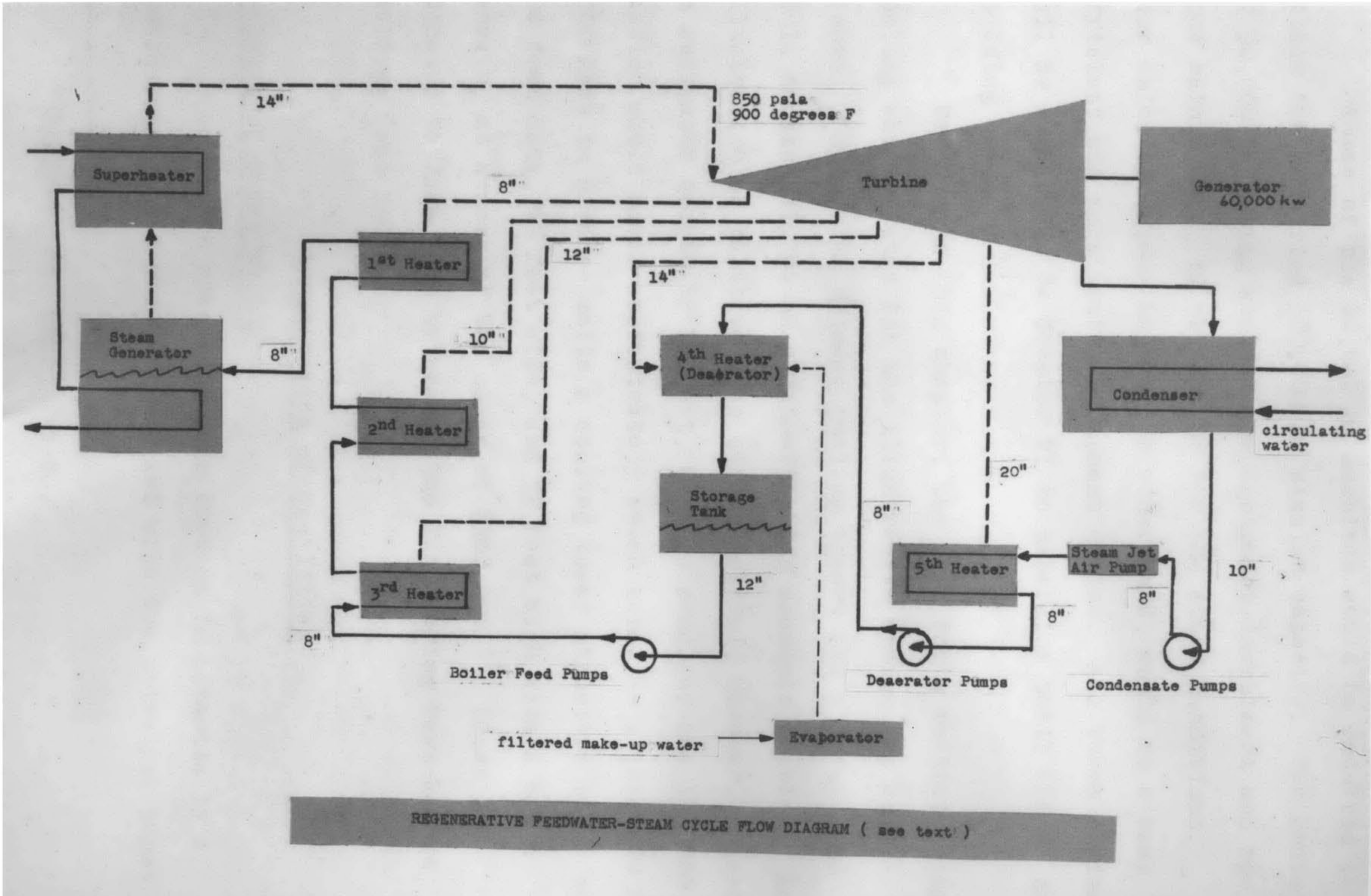
[13]Gaffert, op. cit. 81-2.

[14]The sizes of piping and heaters are based upon the feed water system described in The Watts Bar steam plant. TVA. (1949).



SIMPLIFIED ILLUSTRATIONS OF TWO REACTOR CONCEPTS (SEE TEXT FOR REFERENCES)

Figure 6



REGENERATIVE FEEDWATER-STEAM CYCLE FLOW DIAGRAM (see text)

Figure 7

Three of the 60,000 kw machines would be required to attain the specified 180,000 kw station capacity. Two units of 90,000 kw rating would lower equipment investment and reduce maintenance, if obtainable for the steam conditions. Four units of 40,000 kw, on the other hand, would be a less efficient and more costly equipment choice. All three choices will be considered in Chapter VI to determine their effect on building costs.

Earlier in this chapter, the need for a recirculating cooling water system for the illustrative design was established. The choice between cooling towers and a spray pond would necessarily be an engineering and economic problem. An illustration of relative size can be helpful, however. Based on estimates quoted by Gaffert, a spray pond for the 180,000 kw station would cover approximately seven acres -- a pond 300 by 1000 feet in size -- while a cooling tower structure might be 700 feet long, 63 feet wide, and 32 feet high with a basin beneath, at a cost of the order of $360,000.[15] (Cost is adjusted to June 1955 by use of the Engineering News-Record Building Cost Index.)

Organization of Facilities

Analysis of Organization

The modern steam-electric station is essentially a continuous-process production plant with the principal input

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[15]Gaffert, op. cit. 136-40.

being energy in the form of solid fuels, nuclear or chemical, and the output being energy in the form of electric power of high voltage. Figure 8 is a flow diagram of the production process. It should be noted that while the principal flow is straight-through, there are many recirculating loops involved in the energy transfer and a part of the final electrical energy output is diverted back to power the process.

An organizational chart is presented in Figure 9 showing the number of employees needed for station operation and delineating their responsibilities. Although the total number of employees is large, the ratio of employees to capital investment is very low, being of the order of one employee for each $200,000 of investment. The implication of this fact is that the average employee has large responsibility -- thus that the power station is a prime example of mechanization, where human effort is not utilized directly in the process but is required for control and maintenance. The supervisory nature of the operators' work should be reflected in the design of work stations and employee facilities.

The personnel organization has been determined from information on personnel requirements for a conventional steam-electric station[16] and for a reactor installation.[17] The <u>employees per kw</u> index often used for power stations indicates that this organization is large, being 1.15 employees

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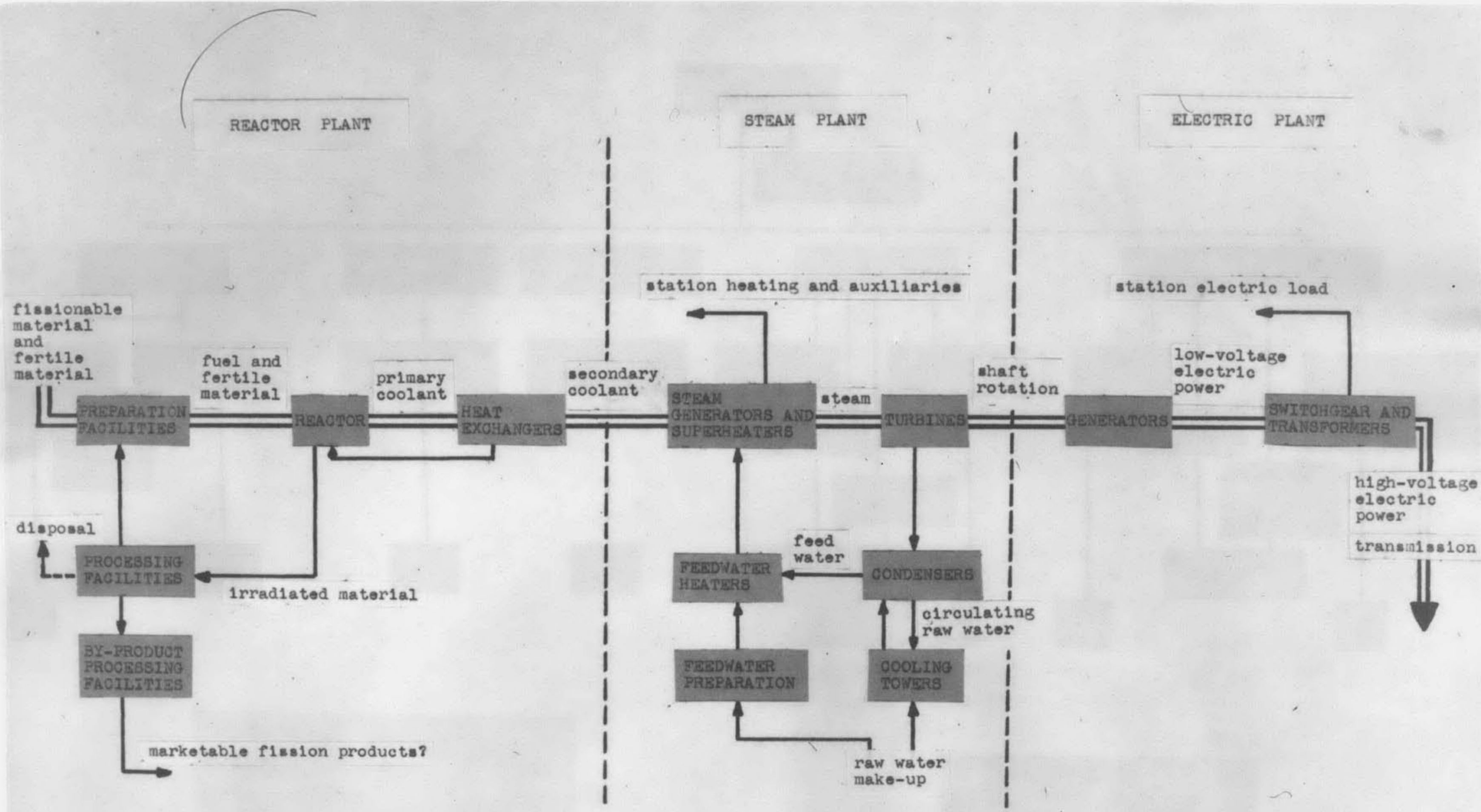
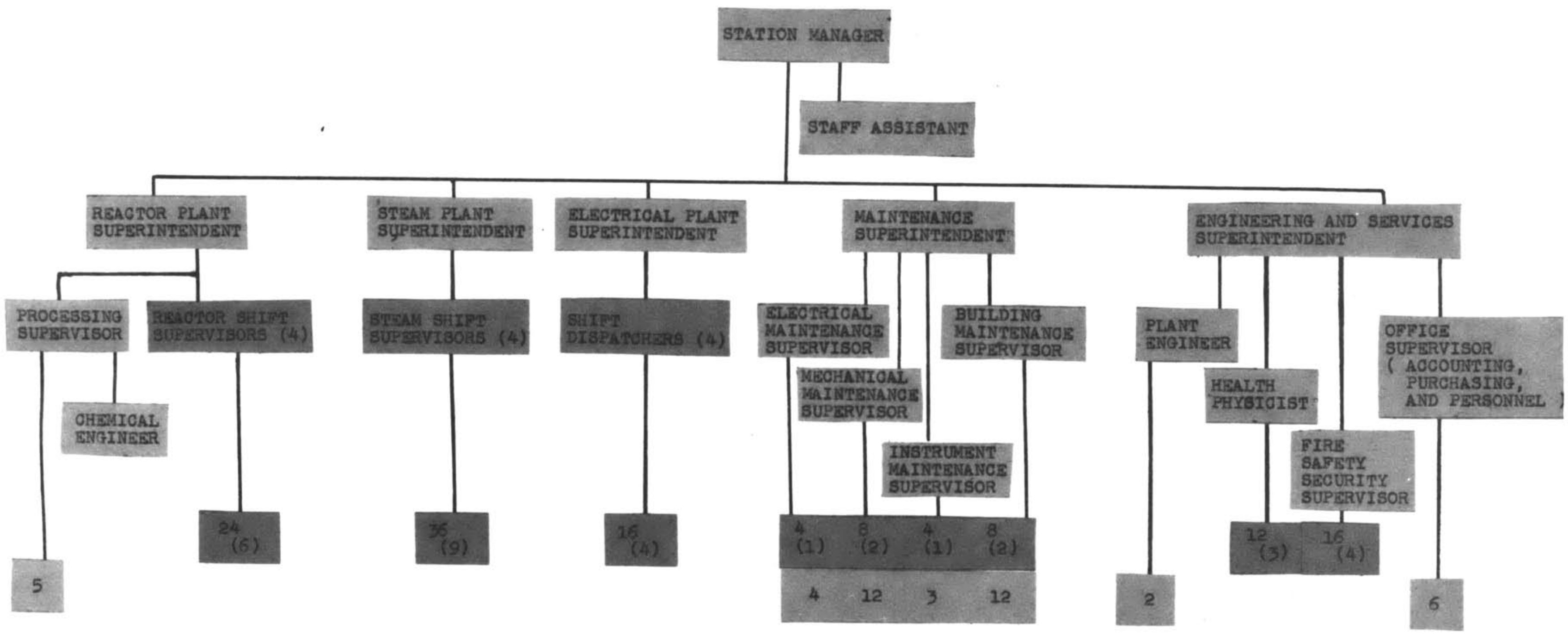
[16] The Watts Bar steam plant. TVA. (1949).

[17] R. L. Doan. Organization and staffing of the materials testing reactor project. Nucleonics. 10-13, March 1953.



FLOW DIAGRAMS FOR NUCLEAR-REACTOR STATION ELECTRIC POWER PRODUCTION

Figure 8



DAY SCHEDULE (including secretaries)	67
4 SHIFT SCHEDULE @ 35	140
TOTAL WORK FORCE	207
DAYTIME OCCUPANCY	102

DENOTES SHIFT SCHEDULE

DENOTES DAY SCHEDULE

STATION PERSONNEL ORGANIZATIONAL CHART

Figure 9

per kw compared to the usual 0.5 to 1 employee per kw for newer conventional stations. This is partially due to the complications imposed by the nuclear systems.

Determination of Space Requirements

The production flow and the operating organization have been defined in previous sections; it is also necessary to develop an estimate of the space requirements for the various facilities. In an actual project, organized as described in Chapter IV, these requirements would most likely be developed jointly by the OR group and the client's various departments. In fact, it is vital that they be carefully evaluated and fully approved by the client since they are an important part of the instructions to the design group and any misunderstandings or subsequent changes will cause serious interruptions in the work of the design group. It is also important that these space requirements be developed in such a manner as to give the design group full information and yet all possible latitude. Space requirements for the present illustrative project are tabulated below. They are estimates and are developed from comparisons with related existing facilities wherever possible. Only a partial breakdown is included as the estimates are arbitrary.

1. Administrative and General Offices
   (including conference room, lunchroom, toilets, lounge, and public lobby). . . . 6,000 sq. ft.
2. Control Area and Offices. . . . . 6,500 sq. ft.
3. Employee Facilities
   (including change house, lunchroom, and first-aid dispensary, and based on

simultaneous use by 70 employees) . . . . 5,000 sq. ft.

4. Shop and Garage . . . . .10,000 sq. ft.

5. Isolated Maintenance Shop
(including decontamination area, maintenance shop, and disposal preparation and storage -- only partially enclosed) . . . 5,400 sq. ft.

On the remaining facilities, space requirements have not been determined in advance of design studies.

6. Reactor Enclosure
(including steam-generator equipment)

7. Turbine-Generator Building
(including condensers, feedwater heating and preparation, chemical analysis laboratory, and ventilation equipment)

8. Switchgear and Transformer Yard

9. Cooling Towers and Pump House

10. Processing Facilities
(including receiving and shipping, preparation and processing of reactor supplies and services, and reactor housing ventilation equipment)

11. Entrance Gatehouse and Parking Facilities
(for parking 72 employees' and 10 visitors' cars, with expected traffic of 75 cars during shift change)

12. Process and Sanitary Sewer Plant

More detailed consideration of space requirements for the illustrative design will be discussed in Chapter VII.

CHAPTER VI

ILLUSTRATIVE STUDIES -- DESIGN

The limitations of scope and validity of conclusions as expressed in Chapter V are applicable to the present chapter.

Criteria

Health Hazards

A principal criterion affecting the arrangement of reactor facilities is that of containment of radioactive contaminants. In an actual project, a quantitative criterion could be established for containment, based on the possibility of a reactor mishap resulting in release of fission products, the inventory and activity of fission products in the reactor, the extent and nature of routine release of fission products, the hazard attending such releases, and applicable laws, regulations and restrictions.[1] In the illustrative project being developed, only the qualitative criterion of effective containment will be imposed.

A second major criterion is that of shielding of the lethal radiations associated with nuclear fission and radioactive isotopes. Again, for an actual project a quantitative criterion would necessarily be established which would be

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[1](Proposed) Licensing of production and utilization facilities. Title 10, chapter 1, part 50, Code of federal regulations. (1955).

based on human tolerance to such radiations.[2] The criterion for this illustrative design will be that of general conformance with previous studies and facilities as reported in the literature and with the general restrictions of proposed regulations. Detailed conformance with these criteria will not be attempted since the necessary evaluations depend on collaboration with nuclear engineering specialists.

Safety, Fire Protection, and Construction

In matters relating to the construction and arrangement of facilities, their safety and fire protection, provisions of the Basic Building Code will be followed as a guide.[3]

Arrangement Studies

Conceptual Design for Sodium Graphite Reactor Housing

A notable feature of the sodium graphite reactor type discussed in Chapter V is the necessary provision for loading and unloading the reactor charge of solid fuel elements. Handling must be by remote control with biological shielding for personnel protection. For the reactor configuration discussed, the fuel elements in the form of long rods would be inserted and removed through the shielding cover above the reactor tank. A conceptual design for the SGR system described in Chapter V is presented in Figure 10. In the design, heavy shielding surrounds the reactors and lighter shielding

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[2](Proposed) Standards for protection against radiation. AEC. (1955?)

[3]Basic building code of the building officials conference of America, inc. (1950).

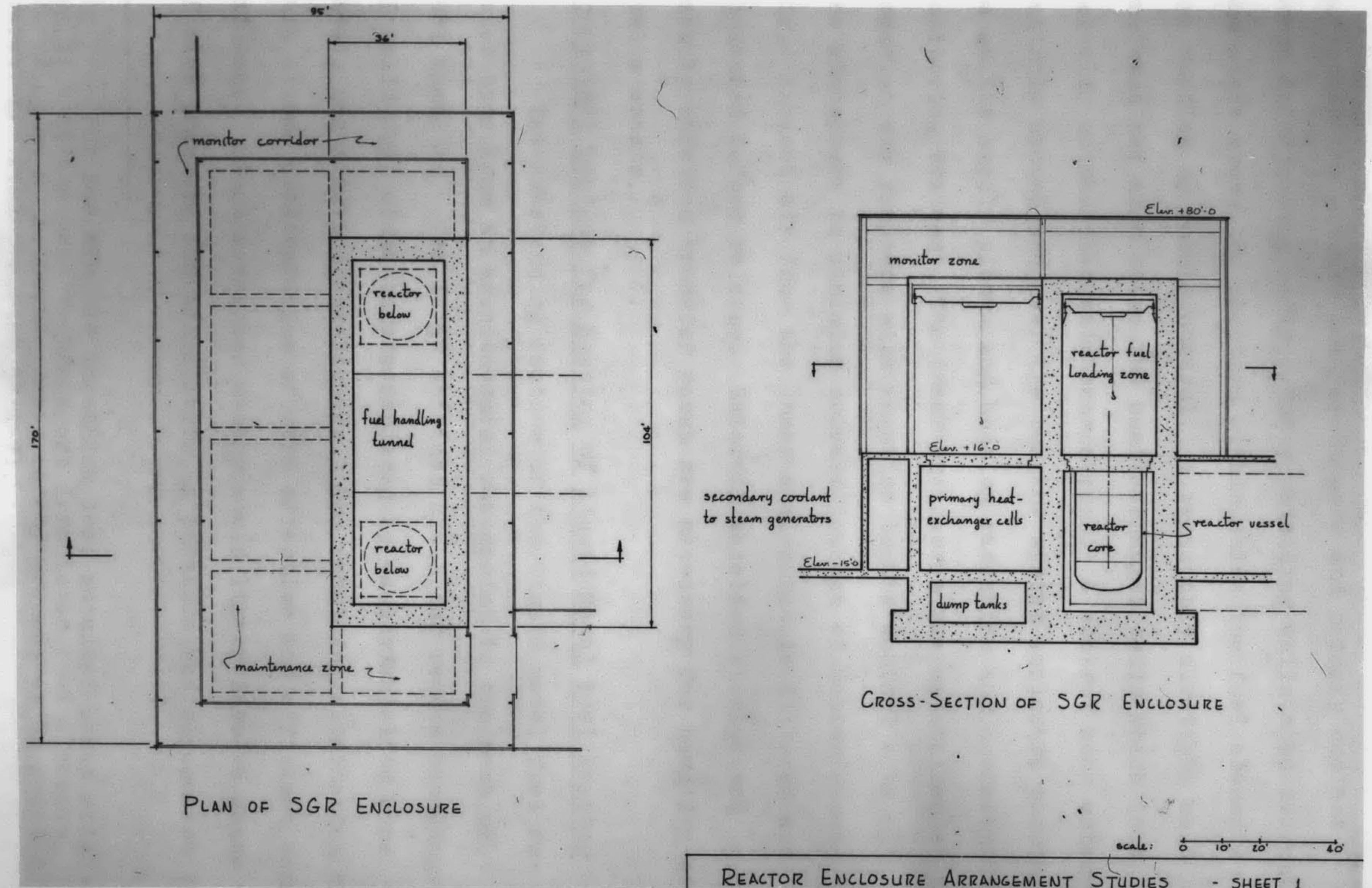
95'
36'
170'
104'
monitor corridor
reactor below
fuel handling tunnel
reactor below
maintenance zone
PLAN OF SGR ENCLOSURE
Elev. +80'-0
monitor zone
reactor fuel loading zone
Elev. +16'-0
secondary coolant to steam generators
primary heat-exchanger cells
reactor core
reactor vessel
Elev. -15'-0
dump tanks
CROSS-SECTION OF SGR ENCLOSURE
scale: 0 10' 20' 40'
REACTOR ENCLOSURE ARRANGEMENT STUDIES - SHEET 1

Figure 10

surrounds the primary heat exchangers and primary coolant pumps in adjoining cells. Heavy shielding walls also surround the space above the reactors within which the fuel elements are handled by remote control. A reasonably air-tight wall encloses the area above the heat exchanger cells which is a normally uninhabited maintenance zone. A control zone extends entirely around and over the reactor system enclosure serving as an air supply plenum and housing radiation and contamination monitoring systems. The inner enclosures are maintained at a negative air pressure with relation to the control zone and the atmosphere to minimize outward leakage of contaminated air. Exhaust air from the inner enclosures is filtered and monitored before release. External shielded storage and heavily shielded transfer casks are necessary for handling of fuel elements.[4]

Conceptual Designs for Housing of Liquid Metal Fuel Reactor

The outstanding feature of the liquid metal fuel reactor type from an architectural standpoint is the ease of fuel handling. The large shielded areas for remote handling of solid fuel elements are replaced by easily shielded pipe chases for handling the liquids. The resulting elimination of bulk allows consideration of more effective and efficient containment. Since a reactor mishap would likely involve gases of high pressure and temperature, a pressure vessel concept is

[4]For the MTR, 14 in.-thick lead-shielded casks weighing 11 tons are used to transport irradiated fuel elements, according to R. L. Doan. Basic safety procedures in reactor operation. ASME preprint 54-A-71.

appropriate.

Arrangement Number 1. The most efficient pressure vessel for gases is a sphere. It contains the greatest volume per unit of surface area of any geometrical solid and provides for efficient resolution of stresses due to pressure loading. Arrangement 1, consisting of a steel spherical housing of 140 foot diameter, is shown in Figure 11. The sphere is depressed slightly into the ground on a saucer-shaped foundation. Space is allocated within the sphere for steam generators and superheaters. By this means the secondary coolant loop, which enters the reactor vessel and will become radioactive, is kept within the containment sphere. An access tunnel and airlock is provided for maintenance use. A derrick tower and boom installed on the vertical axis of the sphere provides access to all equipment locations, as in the earlier arrangement.[5]

Arrangement Number 2. This conceptual design (Figure 12) is essentially a vertical cylindrical pressure vessel -- a form suitable for construction in concrete. As in arrangement 1, space is provided for steam generators and superheaters, and a large access tunnel and air-lock is included since concrete construction would preclude any openings after construction of the walls and dome roof. An overhead crane is provided consisting of a central rotating column and a rotating spider running on rails at the exterior wall and carrying the travelling hoists. The space allocated for equipment and maintenance

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[5]The SIR test reactor at KAPL is enclosed in a steel sphere, according to Sphere is atomic sub lab. Engineering news-record. 32-4, April 9, 1953.

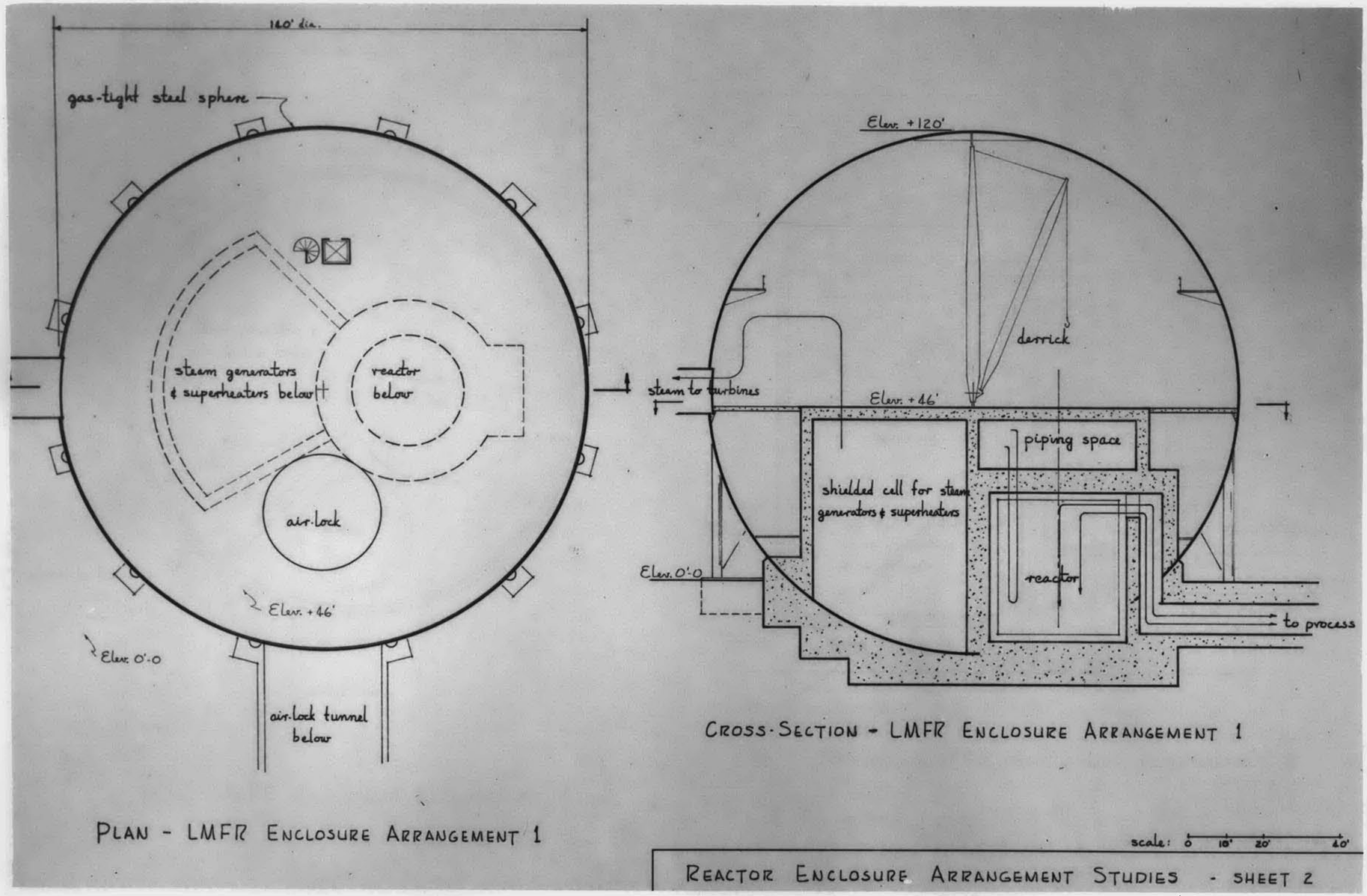

140' dia.
gas-tight steel sphere
steam generators
& superheaters below
reactor
below
air-lock
Elev. +46'
Elev. 0'-0
air-lock tunnel
below
PLAN - LMFR ENCLOSURE ARRANGEMENT 1
Elev. +120'
derrick
steam to turbines
Elev. +46'
piping space
shielded cell for steam
generators & superheaters
Elev. 0'-0
reactor
to process
CROSS-SECTION - LMFR ENCLOSURE ARRANGEMENT 1
scale: 0 10' 20' 40'
REACTOR ENCLOSURE ARRANGEMENT STUDIES - SHEET 2

Figure 11

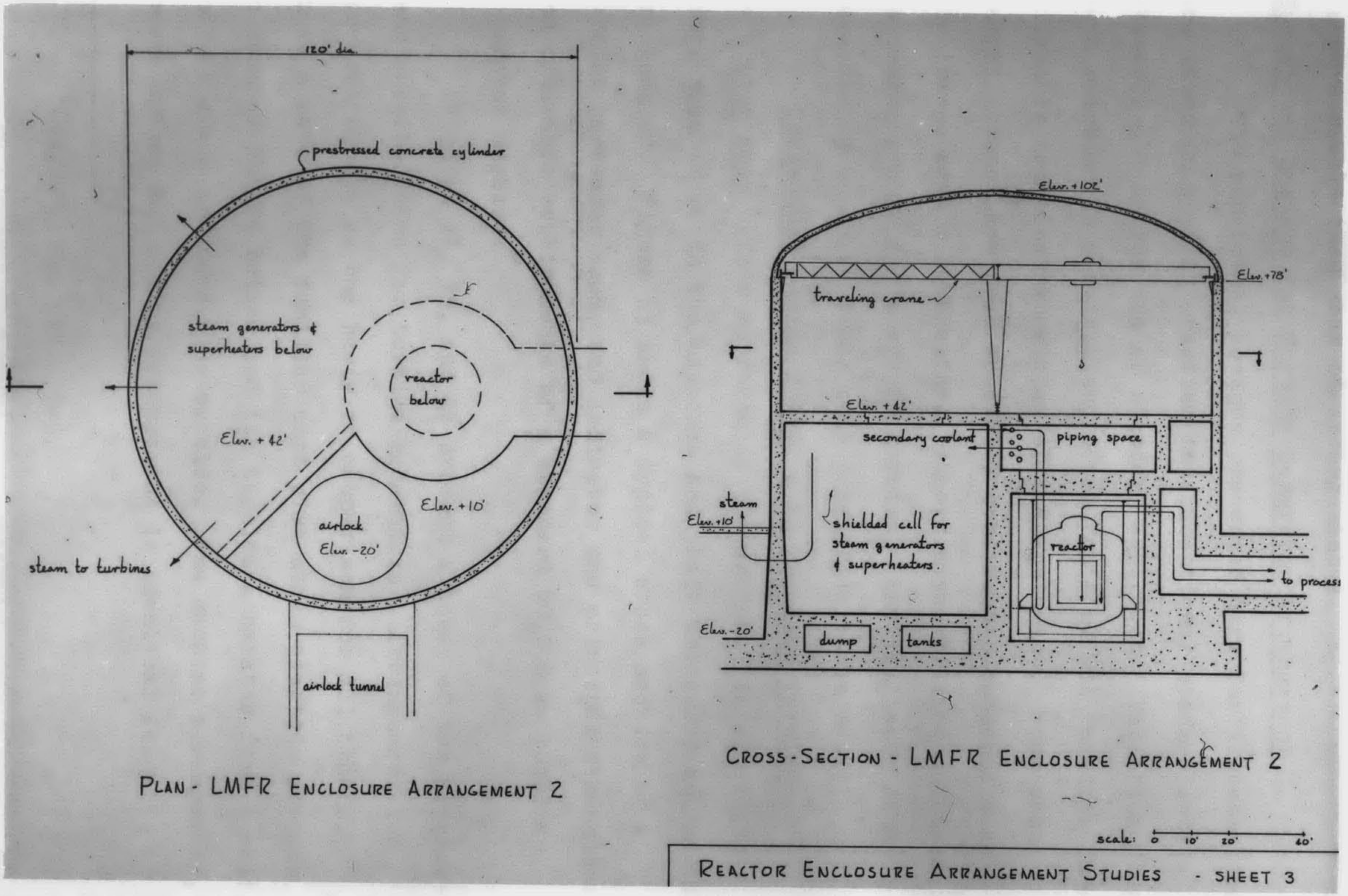

120' dia.
prestressed concrete cylinder
steam generators & superheaters below
reactor below
Elev. + 42'
Elev. + 10'
airlock
Elev. -20'
steam to turbines
airlock tunnel
PLAN - LMFR ENCLOSURE ARRANGEMENT 2
Elev. +102'
Elev. +78'
traveling crane
Elev. + 42'
secondary coolant
piping space
steam
Elev. +10'
shielded cell for steam generators & superheaters.
reactor
to process
Elev. -20'
dump
tanks
CROSS-SECTION - LMFR ENCLOSURE ARRANGEMENT 2
scale: 0 10' 20' 40'
REACTOR ENCLOSURE ARRANGEMENT STUDIES - SHEET 3

Figure 12

is more usable than that of arrangement 1.

Conceptual Designs for Turbine-Generator Arrangement

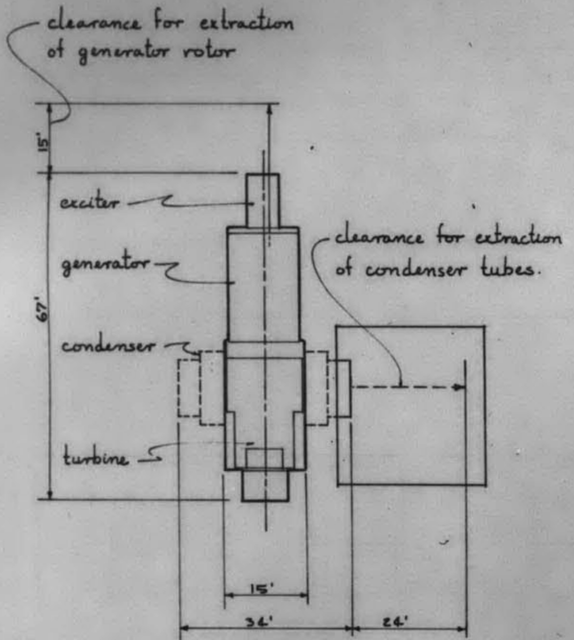
The conceptual designs presented here for illustration are based on typical practice in conventional steam-electric stations and on the use of standard equipment. Variation from such practice is possible and often fruitful but requires considerable technical knowledge of the equipment. Some past installations have used specially constructed condensers as turbine-generator foundations; others have utilized multiple condenser groups for a single turbine. Any realistic study necessarily would consider such possibilities in detail.

Conceptual Design Number 1 -- Enclosed Turbine-Generator Room. This approach is conventional in providing a large room in which the machines and their accessory equipment are located. Figure 13 shows a typical cross-section of a turbine-generator room, and indicates the principal dimensions and clearance requirements of a standard 60,000 kw turbine-generator machine.[6]

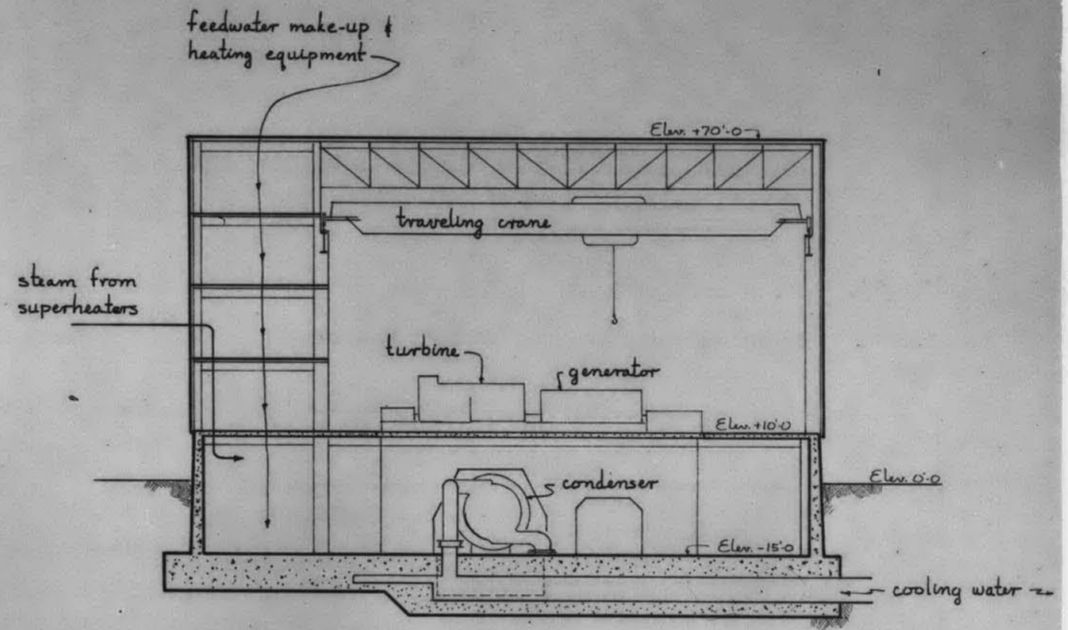
Figures 14, 15, and 16 present a total of ten arrangement possibilities for turbine-generators. Arrangement 1-A has been chosen as the basis of comparison for all others. It is a part of the familiar unit plan steam-electric station in which a single boiler and its turbine-generator form a unit, and units are arranged side by side. The machine arrangement, access space, and piping arrangement is identical for all

---

[6]Gaffert, op. cit. 599.



PRINCIPAL PLAN DIMENSIONS & CLEARANCES
60,000 KW 3600 RPM TURBINE-GENERATOR UNIT



CROSS-SECTION THRU TURBINE-GENERATOR BUILDING
(TYPICAL FOR ARRANGEMENT 1-A)

scale: 0 10' 20' 40'

TURBINE-GENERATOR ARRANGEMENT STUDIES - SHEET 1

Figure 13

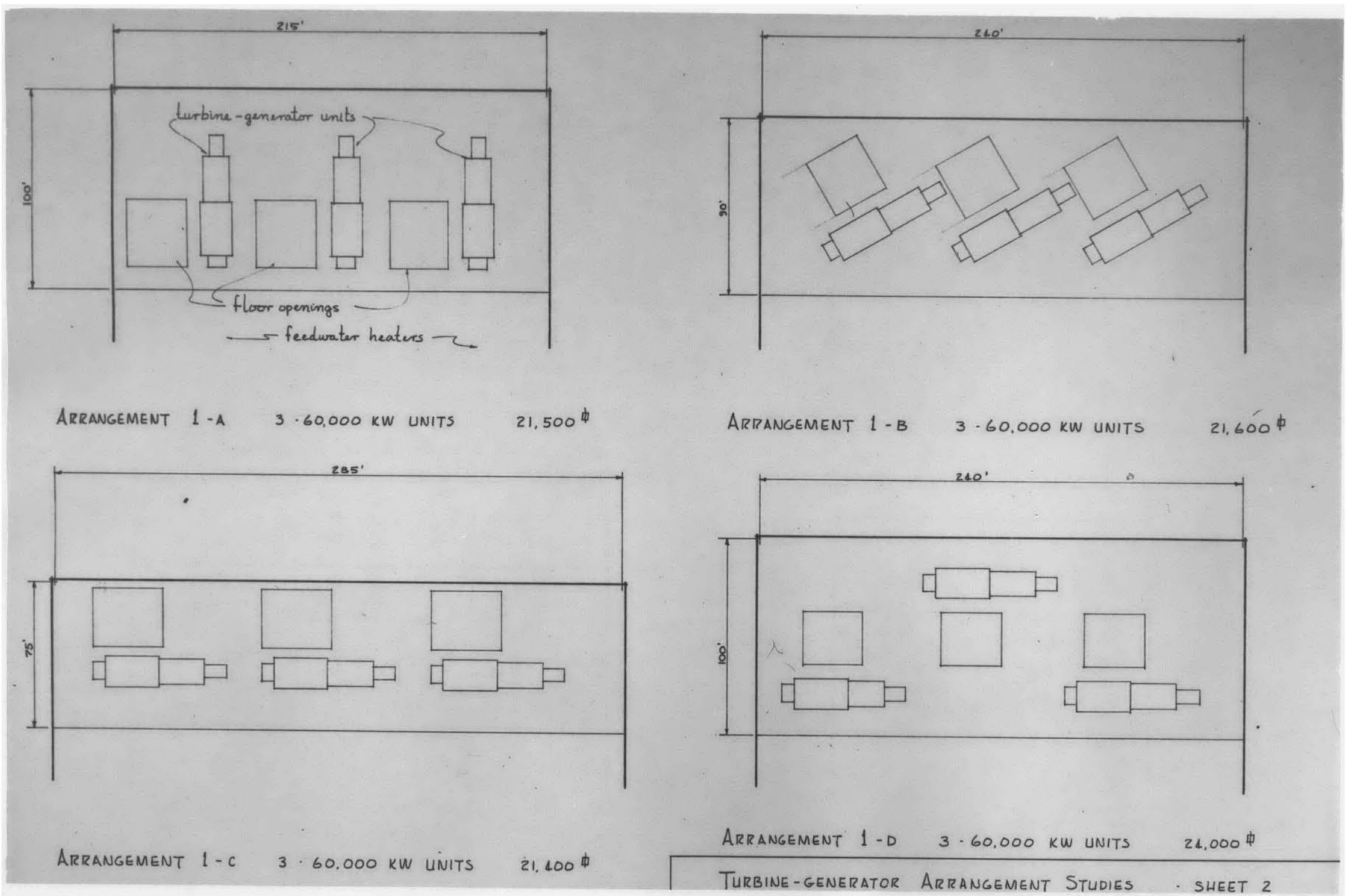

215'
100'
turbine-generator units
floor openings
feedwater heaters
ARRANGEMENT 1-A 3-60,000 KW UNITS 21,500 ϕ
240'
90'
ARRANGEMENT 1-B 3-60,000 KW UNITS 21,600 ϕ
285'
75'
ARRANGEMENT 1-C 3-60,000 KW UNITS 21,400 ϕ
240'
100'
ARRANGEMENT 1-D 3-60,000 KW UNITS 24,000 ϕ
TURBINE-GENERATOR ARRANGEMENT STUDIES · SHEET 2

Figure 14

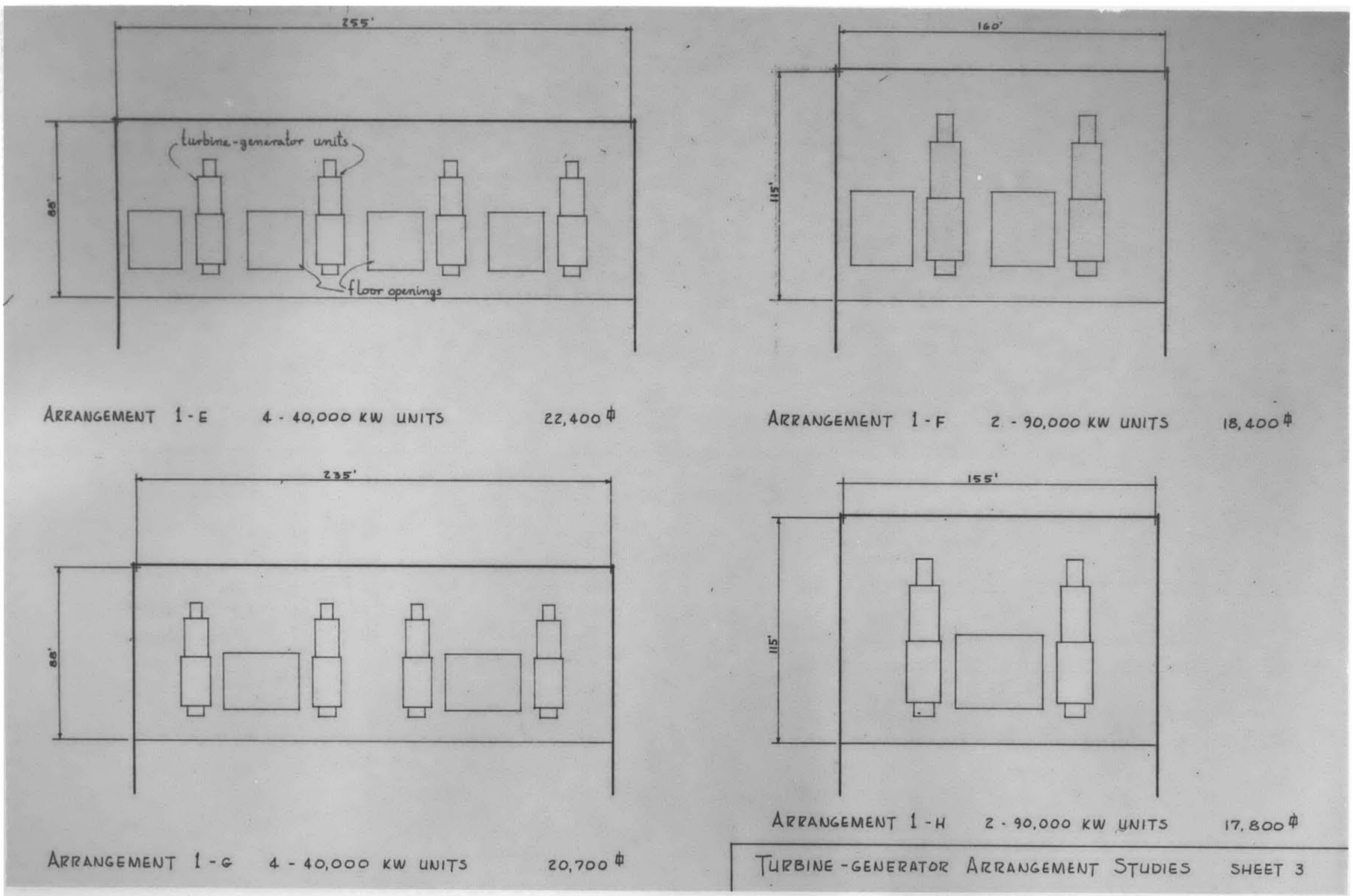

255'
88'
turbine-generator units
floor openings
ARRANGEMENT 1-E 4-40,000 KW UNITS 22,400 ¢
160'
115'
ARRANGEMENT 1-F 2-90,000 KW UNITS 18,400 ¢
235'
88'
ARRANGEMENT 1-G 4-40,000 KW UNITS 20,700 ¢
155'
115'
ARRANGEMENT 1-H 2-90,000 KW UNITS 17,800 ¢
TURBINE-GENERATOR ARRANGEMENT STUDIES SHEET 3

Figure 15

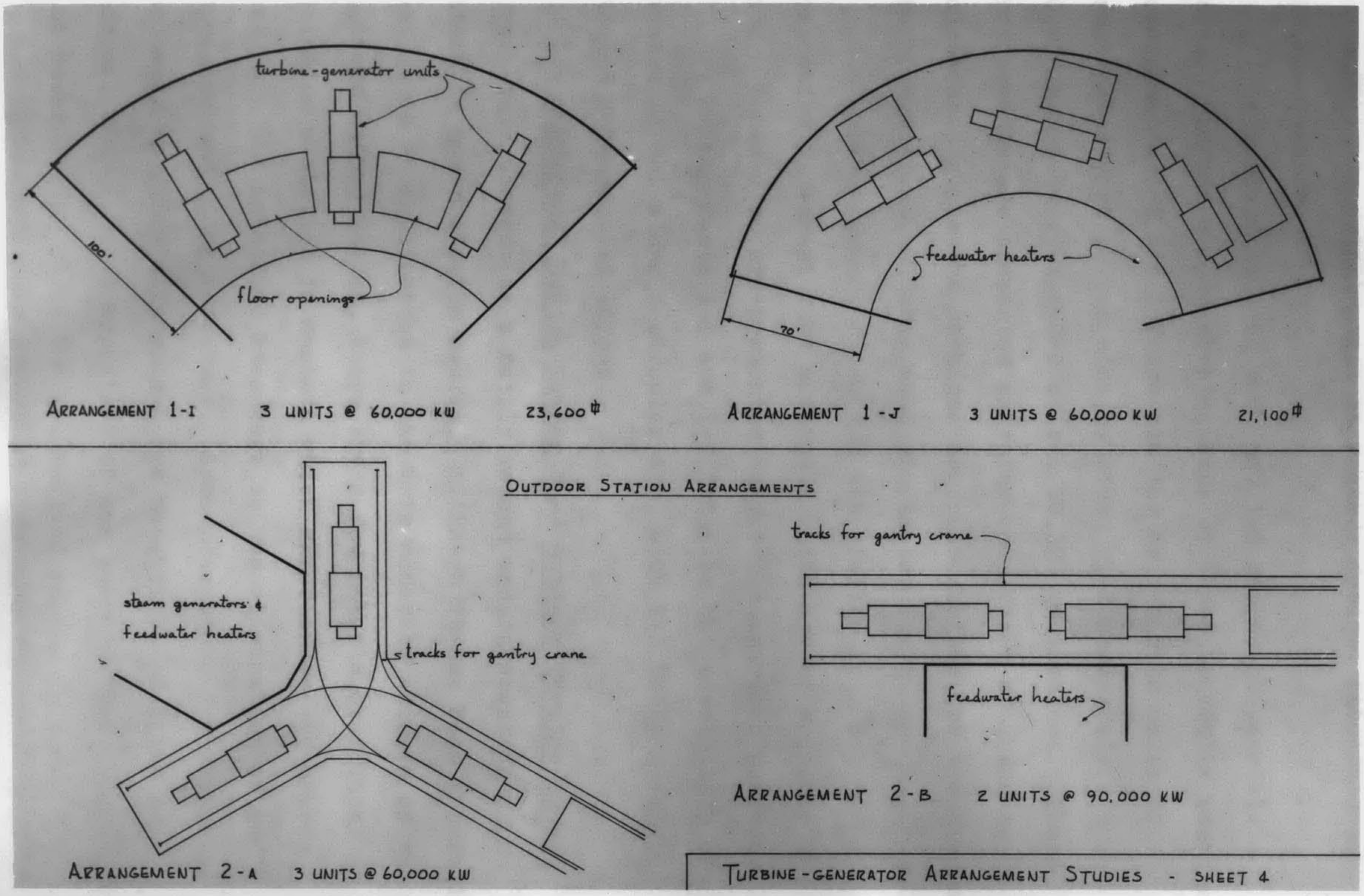

turbine-generator units
floor openings
100'
ARRANGEMENT 1-I
3 UNITS @ 60,000 KW
23,600#
feedwater heaters
70'
ARRANGEMENT 1-J
3 UNITS @ 60,000 KW
21,100#
OUTDOOR STATION ARRANGEMENTS
steam generators &
feedwater heaters
tracks for gantry crane
ARRANGEMENT 2-A
3 UNITS @ 60,000 KW
tracks for gantry crane
feedwater heaters
ARRANGEMENT 2-B
2 UNITS @ 90,000 KW
TURBINE-GENERATOR ARRANGEMENT STUDIES - SHEET 4

Figure 16

units -- an important point as regards design, fabrication, and maintenance.

Arrangements 1-B, 1-C, and 1-D represent possible oblique and end-to-end arrangements of three 60,000 kw machines. Arrangements 1-E and 1-F are similar to 1-A with units of identical layout placed side by side. 1-E consists of four 40,000 kw machines and 1-F of two 90,000 kw machines. These arrangements are presented only for comparison of space requirements, since the machines are poor choices for the assumed steam conditions, as discussed in Chapter V.

Arrangements 1-G and 1-H are similar to 1-E and 1-F respectively, except that alternate units are of opposite hand. These also are presented only for comparison purposes.

Arrangements 1-I and 1-J indicate the possibility of machine layout along a circular arc, with 1-I being a radial and 1-J a tangential layout.

<u>Conceptual Design Number 2 -- Outdoor Turbine-Generators</u>. This concept is a fairly recent and interesting innovation in power station design. Although it has been generally restricted in application to the more moderate climate of the southern United States, there are a few notable exceptions including a station in Montana which experiences -45 degree weather. The principal advantage is the elimination of an expensive enclosing structure. Some provisions for temporary enclosure to allow maintenance are necessary. Judging from informal comments and appraisal of new construction, it appears that power utilities in the New England region do not favor

outdoor installations at this time. Therefore, arrangements 2-A and 2-B shown in Figure 16 are presented only for their interesting possibilities and will not be evaluated further.

Evaluation of Conceptual Designs

Reactors. Three divergent concepts are presented, based on the two reactor systems. In Table 1 the three designs are compared with regard to quantity of ordinary concrete, quantity of special shielding, quantity of structural steel, enclosure and main shell construction cost, and construction time required. The estimates are based on the following unit costs:

Material	Unit Cost Dollars	Source
Ordinary concrete in place	150/c.y.	7
Special shielding concrete in place	250/c.y.	7
Structural steel in place	300/ton	estimate
Building walls (panel) in place	4/s.f.	"
Building roof in place	3/s.f.	"
Steel sphere including supports	600/ton	8
Sphere insulation and covering	2.50/s.f.	estimate
Prestressed and dome concrete in place	200/c.y.	"

These estimates of quantities and cost are extremely rough and are meant to be indicative only of relative construction costs for the three arrangements.

---

[7] James A. Lane. How to design reactor shields for lowest cost. Nucleonics. 57, June 1955.

[8] Sphere is atomic sub lab. Engineering news-record. 32-4, April 9, 1953.

Table 1

COMPARISON OF REACTOR ENCLOSURE CONCEPTS

	2-SGR (240,000 kw Electrical) Concrete Vault	LMFR (180,000 kw Electrical) Steel Sphere Arrangement 1	LMFR (180,000 kw Electrical) Concrete Cylinder Arrangement 2
Ordinary concrete	8000 c.y.	6000 c.y.	8000 c.y.
Special shielding concrete	6000 c,y.	2000 c.y.	2000 c.y.
Structural steel	150 tons	1200 tons	--
Direct construction costs	$3,000,000	$1,900,000	$2,100,000
Cost/kilowatt	$12.50	$10.50	$11.60
Construction time	6 months	4 months	7 months

From inspection of Table 1 it is evident that the costs of the three arrangements are of the same order of magnitude although these estimates favor the two arrangements for the LMFR over the concrete vaults required for the SGR. Between the two possibilities for the LMFR, arrangement 1, the steel sphere, offers an apparent advantage in cost as well as construction time. Also arrangement 1 should prove to provide more adequate containment than arrangement 2. Conversely, arrangement 2 can more readily be joined to other building elements and is somewhat more compact.

Turbine-Generator Arrangements. The outdoor type are not deemed suitable for the New England area and will not be considered.

The ten variations of arrangement 1 can be evaluated by several methods. The most meaningful in this case is probably that of a comparison of their contributions to the cost of the electric energy produced. Such an analysis would consider both fixed costs and operating costs. Operating costs would include costs of equipment maintenance access, control, and building maintenance. The principal variable operating costs would be those concerned with process flow, such as steam piping to the turbines, feedwater, and circulating water. The participation of experienced engineers would be necessary in order to derive reliable estimates for these operating costs; therefore, they will not be considered in this example.

In considering the contributions of final cost to the cost of production for this example, only direct construction costs will be considered. All arrangements will be assumed to require similar structural systems and the height requirements of all arrangements will be assumed identical. As a further simplification only wall perimeter, structural span, and plan form will be considered as variables. The cost of perimeter walls, including foundations, for the basic arrangement is estimated to comprise 10 per cent of the total building cost. The perimeter cost for an arrangement can be considered approximately proportional to the length of the perimeter. Thus,

$$\frac{\text{Perimeter}_x}{\text{Perimeter}_1}\ (0.10) = \text{Perimeter Factor}_x$$

Similarly, the cost of main span structural members for the basic arrangement is estimated to comprise 10 per cent of the total building cost. If the depth of span is assumed fixed, the cost of the main structural members can be considered to vary as the square of the span. Thus,

$$\frac{\text{Span}_x^2}{\text{Span}_1^2}\,(0.10) = \text{Span Factor}_x$$

The remaining 80 per cent of building costs is assumed as fixed on a unit volume basis. The plan form factor is introduced as a multiplier with values estimated on the basis of construction complications introduced by the form. The cost per cubic foot of the basic arrangement 1-A is estimated to be $1.50.[9]

The estimated construction cost per cubic foot of any arrangement is then computed by using the expression

(0.80 + Perimeter Factor + Span Factor) (Form Factor) (Base Cost per Cubic Foot) = Unit Cost in Dollars per Cubic Foot

and consideration of the total volume and the generating capacity for the arrangement leads to the desired unit cost in dollars per kw capacity.

Table 2 is a tabulation of the foregoing analysis for the ten variations of arrangement 1. Examination of the table shows that the difference between the most and least costly arrangements amounts to slightly more than $5.00 per kw. Although this amounts to $900,000 for the 180,000 kw station, it is only 2 to 3 per cent of the total station cost. Thus, any one of the arrangements might be considered feasible under particular conditions of operating costs. Arrangement variation

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[9]See cost analysis, chapter 2 of this thesis.

Table 2

COMPARISON OF ARRANGEMENTS FOR TURBINE-GENERATOR ENCLOSURES

Arrangement Number	Perimeter in feet	Span in feet	Area in square feet	Volume in cubic feet/ kilowatt[c]	Estimated unit cost in Dollars/ cubic foot[d]	Estimated construction cost Dollars/ kilowatt
1-A	650	100	21,500	10.2	1.50	15.30
1-B	660	90	21,600	10.2	1.47	15.00
1-C	720	75	21,400	10.1	1.45	14.70
1-D	680	100	24,000	11.3	1.51	17.10
1-E[a, b]	690	88	22,400	12.0	1.48	17.80
1-F[a]	550	115	18,400	8.7	1.53	13.30
1-G[a, b]	650	88	20,700	11.0	1.47	16.20
1-H[a]	540	115	17,800	8.4	1.52	12.80
1-I[e]	670	100	23,600	11.1	1.66	18.40
1-J[e]	740	70	21,100	9.9	1.59	15.70

[a]Presented only to indicate the effect of four-unit and two-unit installations on enclosure costs.

[b]160,000 kw arrangements -- all other 180,000 kw.

[c]Based on 85 foot height.

[d]Based on $1.50/cubic foot for arrangement 1-A (see text, chapter 2).

[e]Form factor estimated as 1.1. 1.0 used for all preceding arrangements.

1-C is shown to have the lowest construction costs of the three-unit arrangements.

Two further conclusions of general interest can be drawn from the table. Comparison of arrangements 1-E, 1-A, and 1-F, which are respectively four-, three-, and two-unit layouts, shows a consistent decrease in building costs in dollars per kw, thus indicating that building costs as well as equipment costs favor the trend toward fewer but larger turbine-generator units. Comparisons of 1-E and 1-G and of 1-F and 1-H indicate that the building cost savings gained by use of left- and right-hand arrangements are greater for stations of four small units than for stations of two large units. One reason for such a difference is that condenser and access clearances vary only slightly throughout a large range of unit sizes.

<u>Choice of Designs for Illustrative Project</u>

The simplified analyses of reactor and turbine-generator arrangements show reactor arrangement 1-[illegible] and arrangement 1-C for three 60,000 kw turbine-generators to be the least expensive of those considered. These arrangements are compatible and will result in a station of separate facilities connected according to their production flow and access requirements.

The combination of reactor arrangement 2 and turbine-generator arrangement 1-J would result in a very compact station plan with short steam lines. However, further development will not be attempted for this illustrative project since reactor arrangement 1-[illegible] appears to have greater merit than arrangement 2.[10]

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[10] One of the reactors developed in the 1952 feasibility studies for the AEC (CEPS-2) used a somewhat similar plan form, according to Nuclear power reactor technology. AEC. (1953), 17-41.

CHAPTER VII

PRESENTATION AND ANALYSIS

Description of Illustrative Design

Index to Drawings

Site Planning

The analysis of site selection and a description of the selected site are included in Chapters IV and V, and will not be repeated here. Location of the station on the site is a result of four considerations.

1. Isolation to Reduce Hazards to Surrounding Areas. The reactor facilities are located centrally on the extensive

site, slightly over 1000 feet from the railroad.

2. Utilization of the Site. The station facilities are located back from the highway bordering the site, on the expectation that future relaxation of isolation restrictions might permit building along the highways of other industrial plants (perhaps utilizing by-products from the station).

3. Orientation. The layout of station facilities permits short, direct railroad sidings with only slight change of track elevation. Automobile access to the station is gained without the necessity of crossing railroad sidings and is kept away from the potentially hazardous portions of the station. Cooling towers and the circulating water storage pond are located on low ground near the river, and away from the station and the sharp bluff which might interfere with breezes. The switchyard is located so that main transmission lines can be routed directly, without circling the station.

4. Future Expansion. The station layout is arranged so that future expansion directly to the south is possible. Thus, another section consisting of reactor and turbine-generator buildings could be attached. In addition, there is sufficient site to the south to allow construction of an entirely separate station unit if desired.

Reactor Enclosure Design

The reactor enclosure is a modification of LMFR arrangement 1 as discussed in Chapter VI, increased in size to 150 feet diameter and having the reactor unit centered rather than eccentrically located. It is accessible from the change house and shop building through an underground tunnel, as well as from the outside. The sphere is a tank of approximately 1 inch thick steel plates. Erection would commence with the supporting columns, followed by the equator band, after which erection of plates would proceed both upwards and downwards as was done on the 225 foot sphere erected for the SIR project.[1] To provide access for welding and welding inspection, it would be necessary to erect the sphere clear of its concrete substructure. For the 225 foot sphere, this was accomplished by placing the topmost 4 feet of substructure concrete after inspection of the sphere. For the proposed 150 foot sphere, however, it appears feasible to erect the sphere 4 feet above its permanent position, jacking it down after inspection (a lift-slab operation in reverse) and thus reducing substructure thickness.

Biological shielding for the reactor, steam generating equipment, and processing equipment is special shielding concrete, using heavy aggregates such as barytes. Although thicker walls of ordinary concrete could be used instead, the heavy concrete has been shown to be more economical for shielding as well as requiring less floor space.[2] The concrete would be placed by pre-placing aggregate in the forms and then pumping the grout; this is necessary because the high-density aggregates separate during conventional mixing and placing.

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[1] Sphere is atomic sub lab. Engineering news-record. 32-4, April 9, 1953.

[2] Lane, op. cit.

The reactor enclosure is sealed by air-locks and is provided with dampers in the ventilation systems so that any release of contamination within the sphere will be contained. Ventilation air for the reactor enclosure and the preparation building is withdrawn through filter banks and exhausted through a tall stack, to assure dispersion of any released containments.

Turbine-Generator Building Design

Arrangement 1-C as discussed in Chapter VI is the basis for layout. The building substructure is poured concrete and the superstructure is steel frame with insulated metal panel exterior walls and metal roof decking, insulation, and built-up roofing.

The turbine-generator machines indicated are General Electric 66,000 kw 3600 rpm machines for 850 psia, 900 degrees F. steam conditions.[3] The turbine-generator foundations are based on design information from General Electric Company.[4] (Only minor differences in machine size and foundation requirements exist among various manufacturers.)

The turbine-generator room crane is of 100-ton capacity, which is just sufficient to lift the generator stator, the heaviest part of the machine. (The total turbine-generator weight is approximately 450 tons.) A secondary hoist of 15-ton capacity is provided on the crane beam also.

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[3]Outline of foundation Loading plan 416TS page 13. General Electric company.

[4]Turbine-generator foundations. General Electric company GET 1749.

The feedwater make-up and heating equipment provided is based on the flow cycle shown in Figure 7, Chapter V. Sizes for the heaters and principal pumps and tanks are estimates, based on equivalent equipment in the Watts Bar plant.[5]

The location of, and access to, turbine-generator building equipment is based in part on observation of the arrangement of two conventional steam stations in the Boston area.

Office and Shop Building Design

The employees' change house is located in the shop building near the parking area. This facility provides a locker room, toilets and showers, and a lunch room-meeting room for operations and maintenance employees. In addition, separate facilities are provided for changing from contaminated work clothing.

The shops are provided with railroad and truck access, and are connected with the turbine-generator building by a corridor adequate for electric lift-truck travel. The shops are not directly connected with the reactor enclosure or preparation building, in order to control contamination. These areas have small tool rooms containing some equipment. Major equipment removed from contaminated areas would be taken to the remote shop for decontamination, after which it could be brought to the shops by rail or truck.

The garage houses pickup and maintenance trucks, a

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[5]The Watts Bar steam plant. TVA. (1949), 237-56.

disposal truck, and an emergency and fire truck. Also the garage has facilities for minor servicing of vehicles.

Administrative and general offices occupy the second floor, above the change house, and are accessible directly from the parking area.

The central control room is located above the office area, occupying the entire third floor. Access to the turbine-generator building is through a connecting bridge link, while access to the reactor enclosure is by elevator to the basement, and through the connecting underground tunnel. The control room brings together control operations for reactor, steam generator and feedwater heating, turbine-generator, and switchyard equipment, thus assuring consistent and efficient operation. Controls are principally electronic, thus the distance between equipment and control is not critical. Closed circuit television permits continuous observation of hazardous maintenance or remote handling of contaminated equipment.

A public entrance lobby for visitors occupies the west end of the second floor. A connecting bridge links the lobby with a visitors' balcony in the turbine-generator room.

The shop and office buildings are of light steel construction similar to the Macomber V-lok system, with lightweight concrete floor slabs, insulated metal panel exterior walls, and metal roof decking with a built-up insulated roof. Solid plaster interior partitions and suspended plaster ceilings are used in the office areas; steel partitions are used in shop areas, with ceilings exposed. The offices, control room, and change house lunchroom are air-conditioned; all other spaces are ventilated and heated.

Design of Minor Facilities

The entrance gate-house is designed to fulfill two functions: control of entrance into the station area (as required by regulations of the Federal Power Commission) and distribution and collection of radiation exposure indicating devices worn by station personnel.

The remote shop provides a place for the decontamination and/or repair of contaminated equipment from the reactor and preparation areas. It is of light steel construction, similar to the maintenance shops.

Circulating pumps and controls for the cooling towers are housed in a small building of light steel construction. The cooling towers are of conventional design with wood fillers and louvers, and have induced draft fans in the top.

Special Considerations and Details

Provisions for Radiation and Contamination Control.

Normal egress from radiation zones or zones of likely contamination in the reactor enclosure and the preparation building is through the underground tunnel to the change house. Frequent monitoring of all such spaces as well as the tunnel will serve to limit the extent of any contamination. Air monitoring devices will constantly sample the air in reactor and preparation spaces and airlocks, warning of above-normal activity levels. Equipment at entrances to contaminated (or potentially contaminated) zones will permit personnel leaving these zones to check their clothing and shoes, and to detour through the contaminated change room if necessary. Only the reactor enclosure, the preparation building, and the remote shop will be controlled zones. Radiation exposure indicating devices will be worn by all station personnel and checked regularly.

Acoustics. The largest source of noise and vibration in the station are the turbine-generators. Boiler feed pumps, condensate pumps and other large equipment are also powerful sources. In general, structure-borne vibration is not a serious problem, since most large vibrating equipment items are at foundation level and can be damped by massive foundations. Vibrations transmitted through pipes, conduits and ductwork and later radiated as sound can be attenuated by proper expansion joints and resilient mountings. Air-borne sound levels resulting from the sources cannot be easily lowered, since the station equipment rooms are large open spaces. However, the levels are not high enough to cause more than annoyance, and those areas are not continuously occupied.

Some modern power stations are arranged with control rooms and offices opening directly off equipment spaces. Extensive treatment including double glazing and heavy gasketed doors is necessary to reduce sound levels sufficient for office conditions in such arrangements. In this illustrative design a more complete separation is made, whereby offices and control room are housed in a separate building, with minimum structural connection to the equipment buildings. With gasketed doors installed at both ends of connecting passages, a suitably low background level can be assured in the office and control areas. Although the shops are located in the same structure with the office and control areas, all shop equipment will be mounted on isolated slabs on grade and no open paths will exist for air-borne sound.

Color Design. The use of color on equipment and in buildings is an important design consideration. In the equipment and operating areas, bright colors are used for machines and hazardous equipment, and to code process and service piping, while large building surfaces are nearly neutral in color. In the office and control areas, soft subdued colors are used with restricted brightness contrasts as an aid to concentration. In lounges, toilets, lunchrooms and public spaces, bold and lively colors predominate.

Conclusions

Two conclusions are apparent. The first concerns the field of practice. From the studies (and the omissions) of this project it is obvious that the design of nuclear power stations offers a serious challenge to the architect, and that the architect has abilities which are important to a successful project.

The second conclusion is that, at least in the field of industrial architecture, the architect needs to adopt methods and techniques of quantitative analysis in order to cope with complex functional requirements. The economic conditions controlling all industrial activities require that optimal solutions be found if possible. Industry is learning to use the techniques of the field of operations research, and will certainly expect its architects to do as well.

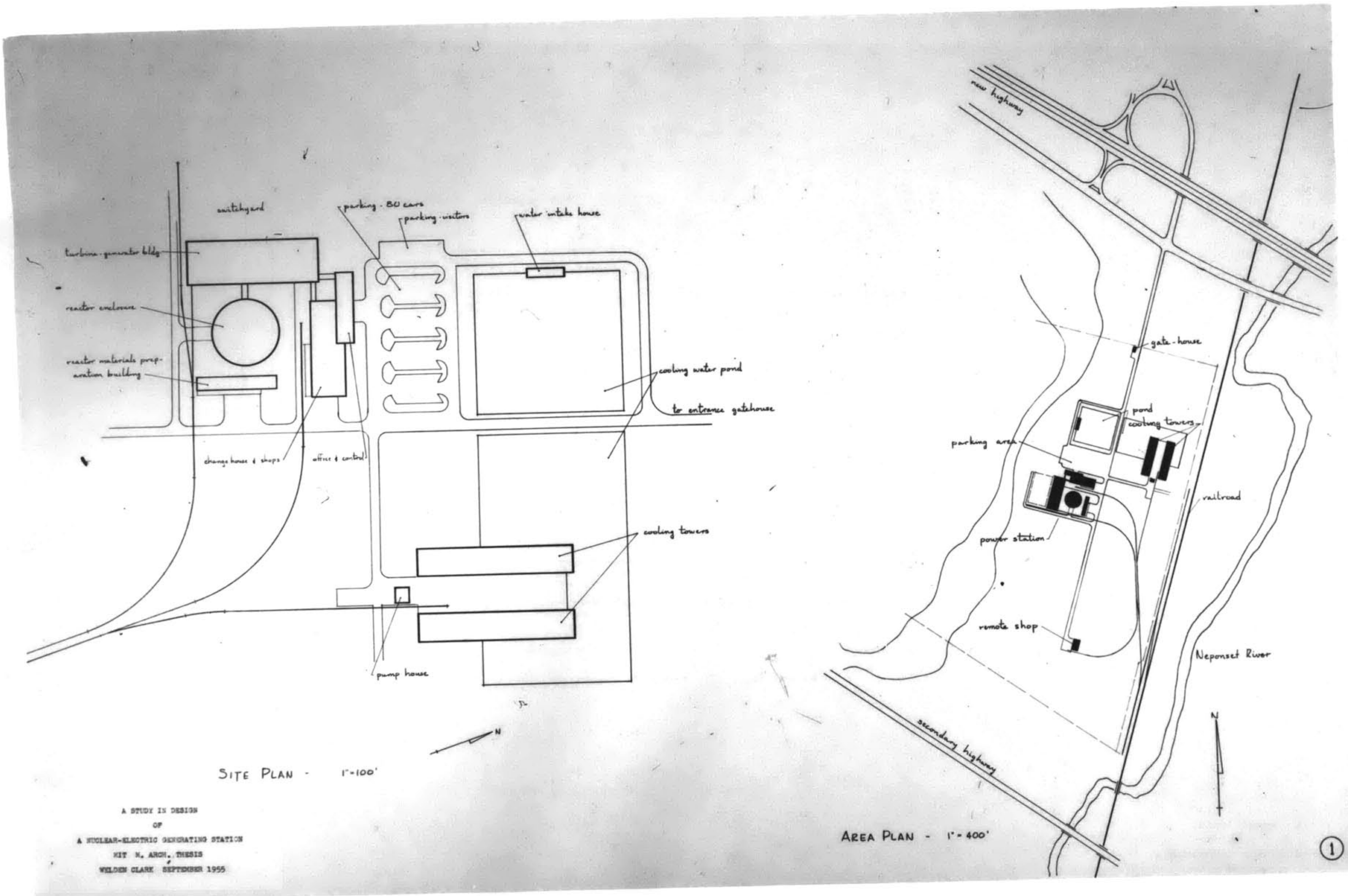

switchyard
turbine-generator bldg.
reactor enclosure
reactor materials preparation building
parking - 80 cars
parking - visitors
water intake house
cooling water pond
to entrance gatehouse
change house & shops
office & control
cooling towers
pump house
SITE PLAN - 1"=100'
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
new highway
gate-house
pond
cooling towers
parking area
power station
railroad
remote shop
Neponset River
secondary highway
N
AREA PLAN - 1"=400'
1

Figure 17

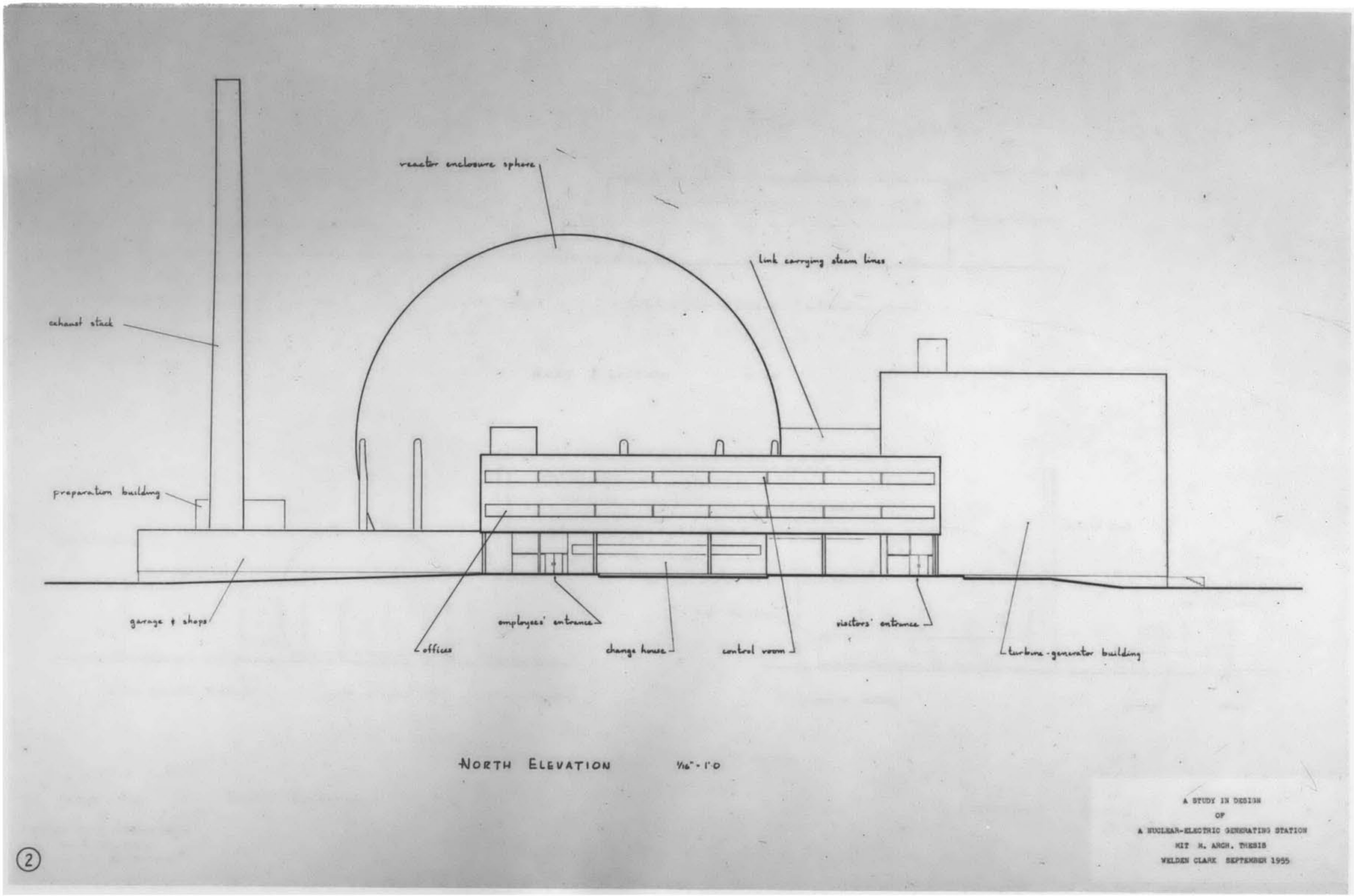

reactor enclosure sphere
link carrying steam lines
exhaust stack
preparation building
garage & shops
offices
employees' entrance
change house
control room
visitors' entrance
turbine-generator building
NORTH ELEVATION 1/16" - 1'0
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
2

Figure 18

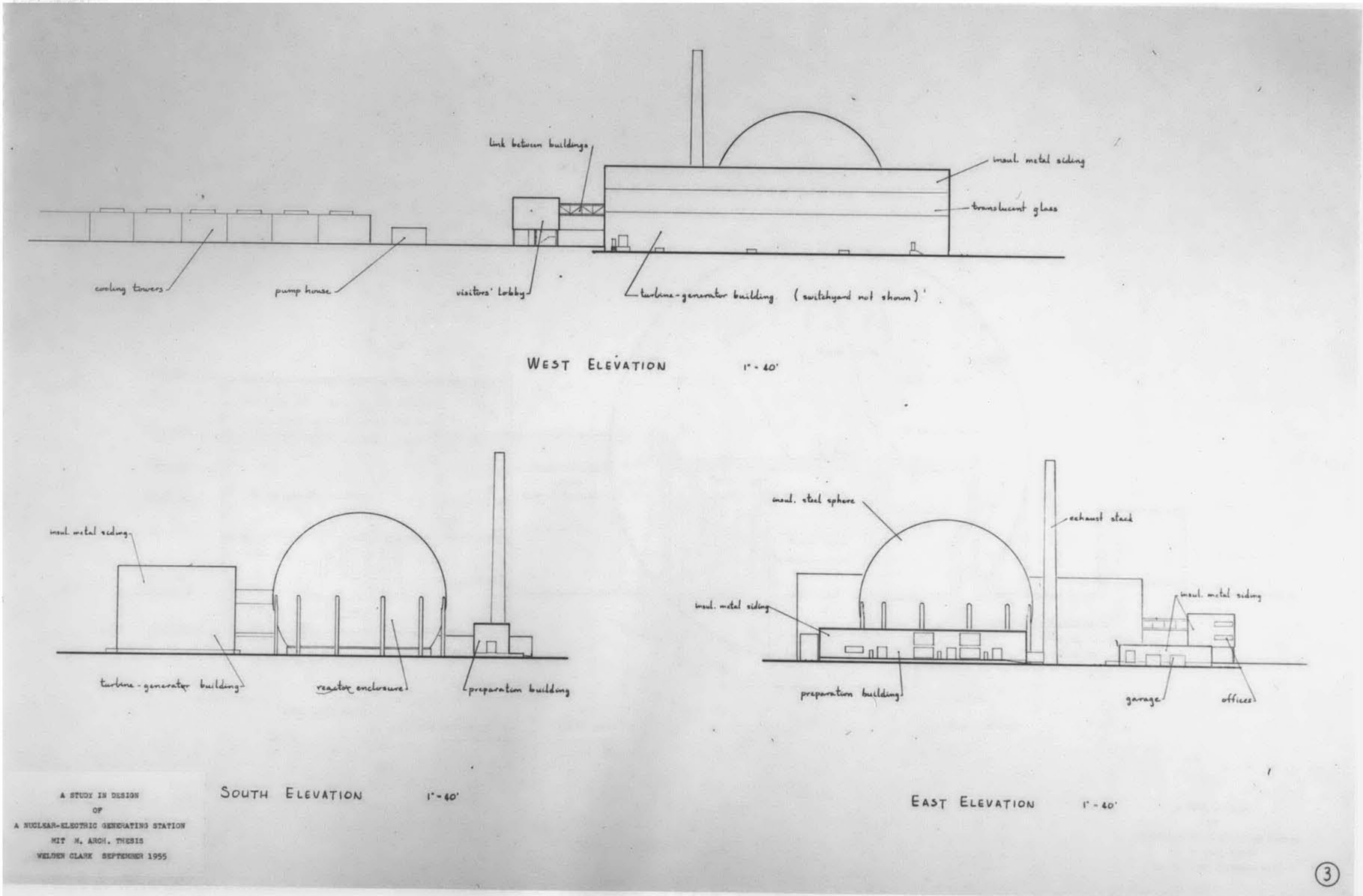

link between buildings
insul. metal siding
translucent glass
cooling towers
pump house
visitors' lobby
turbine-generator building (switchyard not shown)
WEST ELEVATION
1" = 40'
insul. metal siding
turbine-generator building
reactor enclosure
preparation building
insul. steel sphere
exhaust stack
insul. metal siding
insul. metal siding
preparation building
garage
offices
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
SOUTH ELEVATION
1" - 40'
EAST ELEVATION
1" - 40'
3

Figure 19

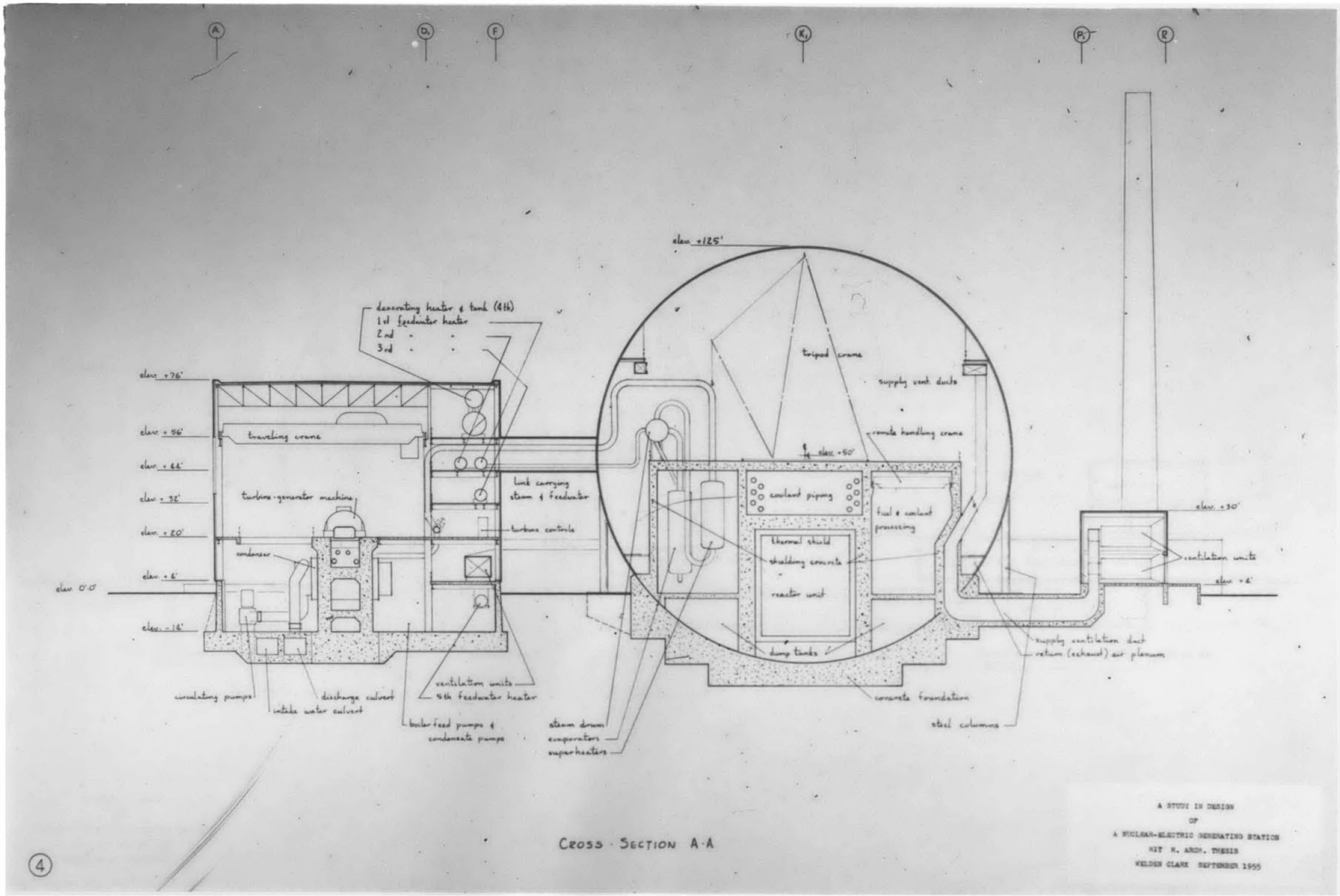
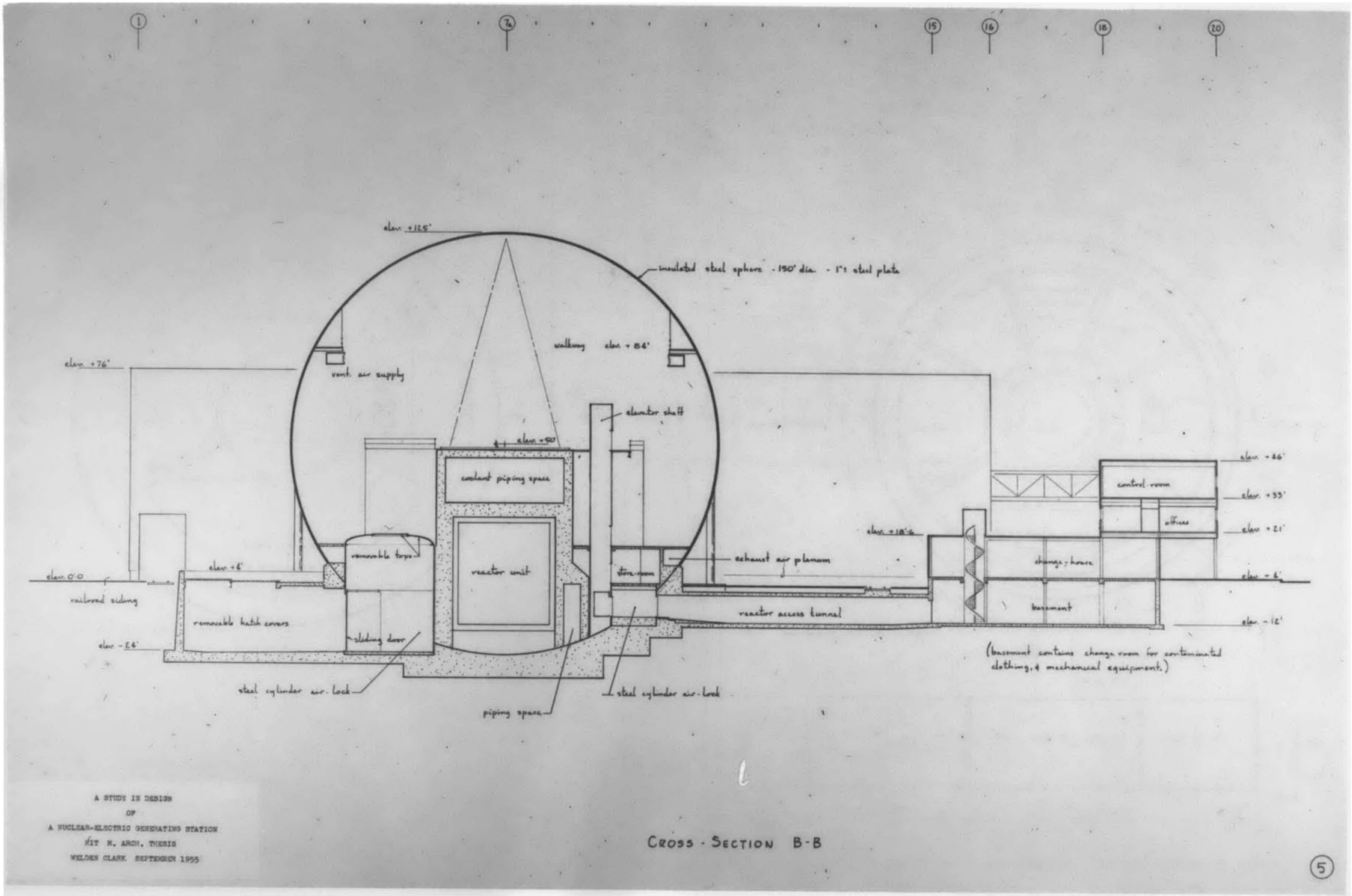
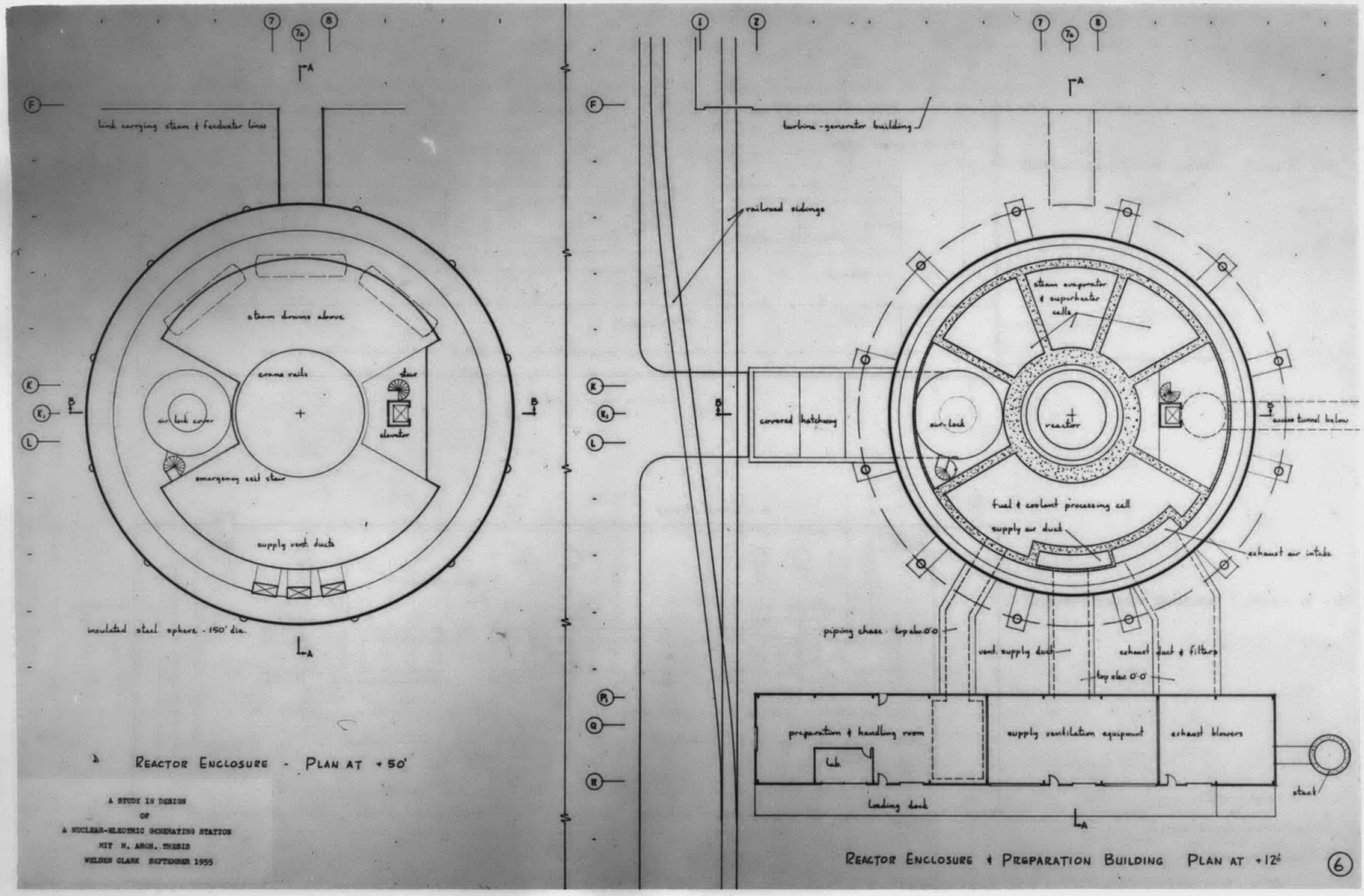

A
D1
F
K1
P1
R
elev. +125'
elev. +76'
elev. +56'
elev. +44'
elev. +32'
elev. +20'
elev. +6'
elev. 0'0"
elev. -14'
deaerating heater & tank (4th)
1st feedwater heater
2nd " "
3rd " "
traveling crane
turbine-generator machine
condenser
link carrying steam & feedwater
turbine controls
circulating pumps
intake water culvert
discharge culvert
ventilation units
5th feedwater heater
boiler feed pumps & condensate pumps
steam drum
evaporators
superheaters
tripod crane
supply vent. ducts
remote handling crane
elev. +50'
coolant piping
fuel & coolant processing
thermal shield
shielding concrete
reactor unit
dump tanks
concrete foundation
steel columns
supply ventilation duct
return (exhaust) air plenum
elev. +30'
ventilation units
elev. +4'
CROSS SECTION A-A
4
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955

Figure 20



elev. +125'
insulated steel sphere - 150' dia. - 1"± steel plate
walkway elev. + 84'
vent. air supply
elev. +76'
elevator shaft
elev. +50'
coolant piping space
reactor unit
removable tops
elev. +6'
elev. 0'-0
railroad siding
removable hatch covers
sliding door
elev. -24'
store-room
exhaust air plenum
reactor access tunnel
elev. +18'-6
control room
offices
change-house
basement
elev. +46'
elev. +33'
elev. +21'
elev. +6'
elev. -12'
(basement contains change room for contaminated clothing, & mechanical equipment.)
steel cylinder air-lock
piping space
steel cylinder air-lock
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
CROSS - SECTION B-B
5

Figure 21



link carrying steam & feedwater lines
steam drums above
crane rails
stair
air lock cover
elevator
emergency exit stair
supply vent ducts
insulated steel sphere - 150' dia.
REACTOR ENCLOSURE - PLAN AT +50'
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
turbine-generator building
railroad sidings
steam evaporator & superheater cells
covered hatchway
air lock
reactor
access tunnel below
fuel & coolant processing cell
supply air duct
exhaust air intake
piping chase top elev 0'0"
vent. supply duct
exhaust duct & filters
top elev 0'0"
preparation & handling room
lab
supply ventilation equipment
exhaust blowers
stack
loading dock
REACTOR ENCLOSURE & PREPARATION BUILDING PLAN AT +12'
6

Figure 22

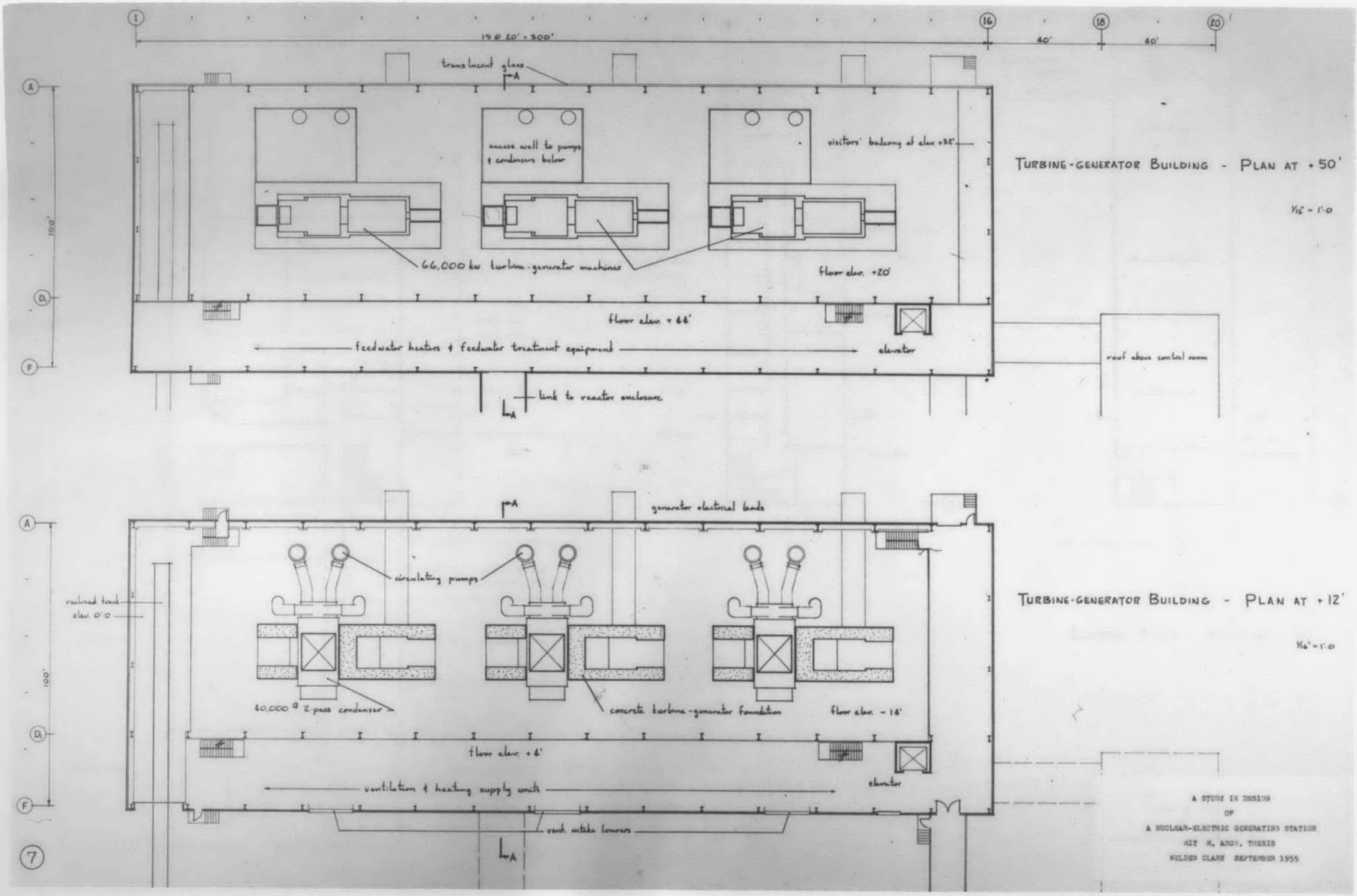
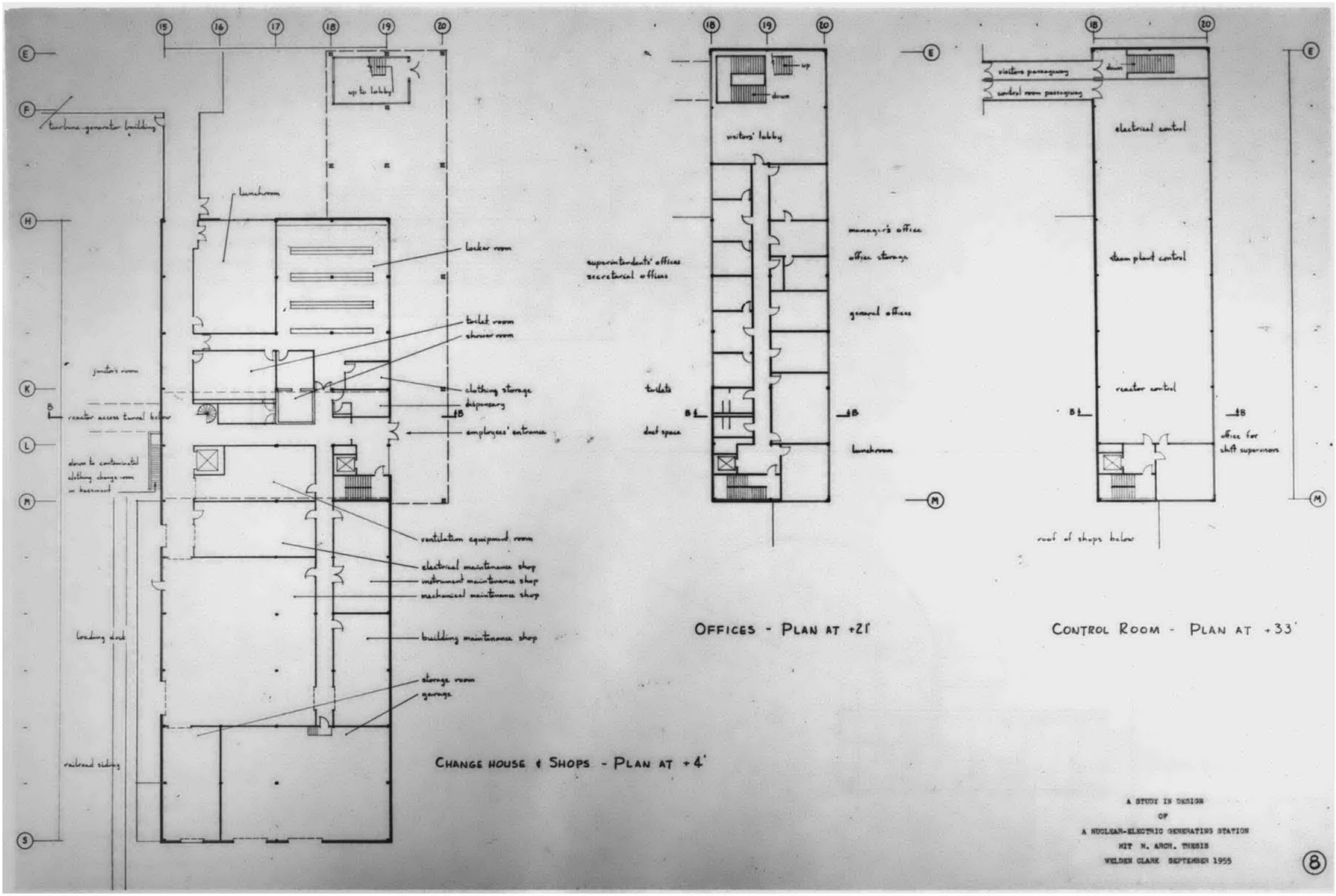

15 @ 20' = 300'
40'
40'
translucent glass
access well to pumps
& condensers below
visitors' balcony at elev. +32'
TURBINE-GENERATOR BUILDING - PLAN AT +50'
1/16" = 1'-0
66,000 kw turbine-generator machines
floor elev. +20'
floor elev. +44'
feedwater heaters & feedwater treatment equipment
elevator
roof above control room
link to reactor enclosure
generator electrical leads
circulating pumps
railroad track
elev. 0'0
TURBINE-GENERATOR BUILDING - PLAN AT +12'
1/16" = 1'-0
60,000 # 2-pass condenser
concrete turbine-generator foundation
floor elev. -16'
floor elev. +6'
ventilation & heating supply units
elevator
vent. intake louvers
100'
100'
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955

Figure 23



turbine generator building
up to lobby
lunchroom
locker room
toilet room
shower room
janitor's room
clothing storage
dispensary
reactor access tunnel below
employees' entrance
down to contaminated clothing change room in basement
ventilation equipment room
electrical maintenance shop
instrument maintenance shop
mechanical maintenance shop
loading dock
building maintenance shop
storage room
garage
railroad siding
CHANGE HOUSE & SHOPS - PLAN AT +4'
up
down
visitors' lobby
manager's office
office storage
superintendents' offices
secretarial offices
general offices
toilets
duct space
lunchroom
OFFICES - PLAN AT +21'
visitors passageway
control room passageway
down
electrical control
steam plant control
reactor control
office for shift supervisors
roof of shops below
CONTROL ROOM - PLAN AT +33'
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK SEPTEMBER 1955
8

Figure 24

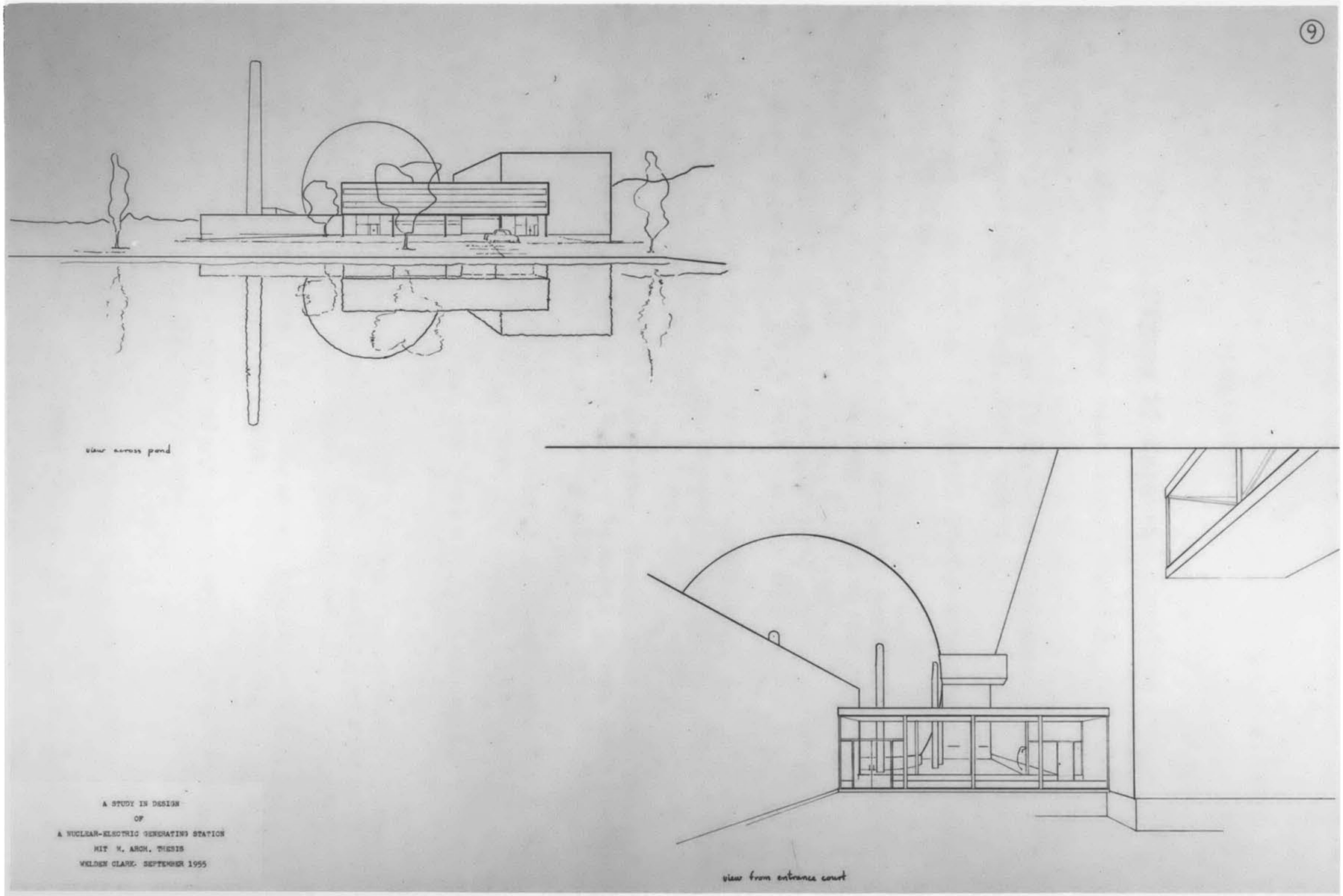

9
view across pond
view from entrance court
A STUDY IN DESIGN
OF
A NUCLEAR-ELECTRIC GENERATING STATION
MIT M. ARCH. THESIS
WELDEN CLARK· SEPTEMBER 1955

Figure 25

Figure 26 deleted

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APPENDIX

APPLICATIONS OF OPERATIONS RESEARCH TECHNIQUES TO SPECIFIC ARCHITECTURAL PROBLEMS

In the first chapter of this work it was suggested that the _useful_ (as opposed to the _esthetic_) conditions to be satisfied in an architectural problem can be compared to the variables in a mathematical formulation. Later in Chapter III, some of these mathematical formulations were discussed. In this appendix two specific problems will be formulated, and one will be solved for an illustrative case.

An Optimization Problem

The organization (arrangement) of the various facilities for an industrial plant must be combined so that the entire plant functions efficiently. For a nuclear power station there are three parameters to be considered in any facility arrangement: production process flow, personnel and maintenance traffic, and hazard isolation. Examples of process flows are: railroad delivery of fuel and supplies, transfer of steam from boilers to turbines, flow of cooling water from condensers to cooling towers, and transmission of the generated electricity. Traffic could be defined to include employee access to work stations, and to lunchrooms, etc., as well as automobile and truck traffic. Hazard isolation, in the case of nuclear plants, is chiefly the need for separation, either by shielding or by distance, of personnel from radiations and contamination above accepted tolerances.

It is possible to establish an arrangement which satisfies requirements for any one parameter almost by inspection. With several to consider, however, the problem becomes more complex and the use of mathematical analogues is helpful.

It will be convenient for this problem to express all requirements in terms of their contributions to total generating costs (i.e., the cost of producing a given quantity of electricity, say 1 kwh).

Considering the various facilities as points, the distances between them can be written as

$$z_{ij} \qquad \text{for} \qquad \begin{array}{l} i = 1,2,3,.....l \\ j = 1,2,3,.....m \end{array}$$

where the distance is measured to the i^{th} facility (the receiving facility) from the j^{th} facility (the acting facility).

Next, coefficients must be derived expressing the cost per unit of distance for any given action (flow, traffic, or isolation) between two facilities. These can be denoted as

a_{ij} = process flow coefficient

b_{ij} = traffic coefficient

c_{ij} = isolation coefficient

Having denoted the distance and the unit cost of an action, the total cost of an action between the i^{th} and the j^{th}

facilities can be written as

$$C_{A_{ij}} = a_{ij}z_{ij}$$

$$C_{B_{ij}} = b_{ij}z_{ij}$$

$$C_{C_{ij}} = c_{ij}z_{ij}$$

and the total cost of an action for all facilities will be

$$C_A = \sum_{i=1}^{l} \sum_{j=1}^{m} a_{ij}z_{ij} \qquad (1)$$

$$C_B = \sum_{i=1}^{l} \sum_{j=1}^{m} b_{ij}z_{ij} \qquad (2)$$

$$C_C = \sum_{i=1}^{l} \sum_{j=1}^{m} c_{ij}z_{ij} \qquad (3)$$

The grand total cost of all actions for all facilities can then be written as

$$C = C_A + C_B + C_C = f(z_{ij}) \qquad (4)$$

This function $C = f(z_{ij})$ must be optimized. The minimum value of C will represent the best feasible operating arrangement.

Considering equations (1), (2), (3), there are three equations in ij unknown independent variables. For $ij < 3$, these would be a set of simultaneous equations sufficient for a direct algebraic solution. However, in general, $ij > 3$, and further relationships are needed to establish a solution. These will be found as limits, or constraints, upon the solution.

The first constraint to consider is that of the minimum possible distance between facilities, expressed as

$$z_{ij} = d_i + d_j \tag{5}$$

where d_i = the least radius of the i^{th} facility

d_j = the least radius of the j^{th} facility

A further set of constraints on the solution are the requirements that all combinations of three points must actually form triangles in space; that is:

$$\begin{aligned} z_{12} + z_{23} - z_{13} &\geq 0 \\ z_{23} + z_{13} - z_{12} &\geq 0 \\ z_{12} + z_{13} - z_{23} &\geq 0 \end{aligned} \tag{6}$$

Thus three inequations are needed to establish this condition for any three points. When there are many points involved, the number of inequations to be written is large.

The set of relationships (1) through (6) represent the formulation of a problem in linear programming. All that remains is to establish values for the coefficients a_{ij}, b_{ij} and c_{ij}, and to establish the radii (approximations) of the various facilities, in order to proceed with the solution. Several methods exist for solution, one being described in Charnes.[1] The validity of these methods is dependent on assumptions of linear relationship for the various flows.

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[1] A. Charnes, W. W. Cooper and A. Henderson. An introduction to linear programming. (1953).

A simplified case of the described organization problem was solved to test the formulation, and an optimum feasible solution was obtained. Application of this method to the actual design problem was not undertaken for two reasons:

1. The validity of the results is dependent on the accuracy of the coefficient determinations. The participation of collaborators from other fields would be necessary to derive the coefficients relating to process flows.

2. The complete formulation and solution of a large problem would take a great deal of time and effort. It is, after all, a substitution of mathematical synthesis for the conception and analysis of many preliminary schemes.

One further comment is in order. The mathematical solution is not expected to result in a rigidly established arrangement. The solution obtained will instead serve as a guide which can be interpreted and varied by the designer.

A Waiting Line Problem

Another technique of mathematical analysis which can be successfully applied to architectural problems is the waiting line formulation as described by Morse.[2] The essentials of the waiting line problem used in this example are a random arrival rate, a random serving rate which is independent of the length of the line of arrivals. It is desirable to

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[2]The methods and formulas used in this discussion of waiting line techniques are taken from a lecture by Prof. Morse in Notes from MIT summer course on operations research. (1953), 33-40.

be able to establish a serving rate which will result in a line shorter than a given length for a predetermined percentage of the time. As an example, with an average serving rate of two per minute and an average arrival rate of one per minute the length of the line will be three or less for 94 per cent of the time.

In the nuclear power station there are two obvious examples of the use of the waiting line technique: the hold-up of automobiles at the entrance gatehouse during shift change, and the problem of proportioning change house facilities such as showers. It is obvious that a large number of showers can be provided for fast clean-up but at a low use factor and high initial cost, or a small number of showers could be provided with a high use factor but at a penalty of long waiting lines.

On the assumption that for a short time interval at shift change a steady random arrival rate exists at the entrance gatehouse, this waiting line analysis can be used to determine gatehouse facilities and personnel. If 50 cars can be expected to arrive within a 15-minute interval at shift time, it is possible to provide several means of accommodating them at the gatehouse. One man might handle 60 cars in 15 minutes, while two men could handle 90 cars at one gate in the 15-minute interval. Finally, one man at each of two gates, with a third man handling badges and radiation meters for both, could pass 120 cars in the 15 minutes.

Let

$$A = \text{average arrival rate}$$

$$S = \text{average serving rate}$$

$$\text{where } \frac{A}{S} < 1$$

then the average length of the waiting line is

$$L = \frac{\frac{A}{S}}{1 - \frac{A}{S}}$$

Thus, in this problem, for one gate man the average length of the waiting line would be 5 cars, while for two men it would be 1.25 cars and for three men and two gates it would be 0.72 cars.

One might also wish to know the probability of getting a line longer than a given number of cars, say 8 (the maximum number which could wait without blocking the highway). In the case with only one gate man a line longer than 8 could occur 19 per cent of the time, while for two gate men such a line would occur less than 1 per cent of the time. The use of two men at one gate thus would seem to be a good choice, as it would result in an average line of 1.25 and blocking of the highway entrance less than 1 per cent of the time.